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BIOLOGICAL EFFECT OF MICROWAVES IN OCCUPATIONAL HYGIENE

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BIOLOGICAL EFFECT OF MICROWAVES IN OCCUPATIONAL HYGIENE

(Voprosy gigieny truda i biologicheskogo deistviya elektromagnitnykh polei sverkhvysokikh chastot)

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INTRODUCTION

Radio engineering plays an important role in modern technological progress and there is hardly a field of human activity which does not make use of radio technology.

Important goals in this field were incorporated in the Program of the Communist Party of the Soviet Union adopted by its 22nd Congress.

The development of radio technology has passed through several stages. The first stage began with the invention of radio by Popov (1895—1918). Its distinctive feature was the application of long radiowaves for wireless telegraphy. The second stage (1918—1940) was marked by the invention of the electron tube, the beginning of industrial use of high-frequency currents for surface heating of metals, invention of radiotelephony and the development of short waves.

Finally, the modern stage of development is distinguished by practical utilization of still shorter waves — microwaves (decimeter, centimeter and millimeter waves), as well as pulse techniques. Examples of current developments include an increased range of radio transmission based on reflection of ultrashort waves from meteor trails, radio communication with spaceships and radiolocation of the planet Venus by means of decimeter radiowaves. Work is also proceeding on high-resolution location of objects by radiowaves in the millimeter range, which will provide a detailed panoramic picture of the surroundings on board aircraft or in controllers' offices in airports. Astronomical observations with millimeter waves permitted calculation of the temperatures of the sun and moon in 1957.

More than 65 years ago, Danilevskii proved the existence of a biological effect on remote exposure to electrical energy and advocated the application of electrical energy to medicine and biology. Over the intervening years, the uses of high-frequency electrical fields have developed in the USSR and other countries.

Investigations of short (SW) and ultrashort (USW) waves, aimed at elucidating the nature and mechanism of their biological effects (mainly for physiotherapeutic purposes), did not begin before the end of the 1920's to 1930's (Schliephake, 1932; Pflomm, 1931; Pätzold, 1932; and others). Pätzold (1932—1934) and Suponitskaya (1938) pointed out the promising prospects of utilizing decimeter waves (DW), making possible much lower irradiation intensities than with ultrashort waves.

The first comparative evaluations of the biological effects of USW and DW were provided by Suponitskaya (1938), Malov, Obrosov and Fridman (1940) and Mukhina (1940). The thermal effect of DW was found to occur at considerably lower power and to be much more pronounced than that of USW, and the difference was explained by Suponitskaya as being due to a difference in the resonance-induced vibrations of the molecular structures in the tissues. These investigations marked a new stage in the research on the biological effect of this little-studied region in the electromagnetic spectrum.

In the USA, interest in the biological effects of microwaves in the centimeter range was aroused in 1943 by examination of sailors servicing low-power radar units (Daily, 1943). Later, in 1954, the medical office of the U. S. aircraft industry embarked on dynamic investigations of personnel exposed to microwave emanations (Barron, Love and Barraff, 1956a, b, 1958).

Early investigations, both inside and outside the USSR, of operators exposed to centimeter waves did not reveal any biological effects. This failure was readily explicable. By analogy with the effect of ionizing radiations, the investigators looked for pronounced specific changes, for instance, in the blood, dermal lesions, etc. The failure was natural since attention was concentrated on radar operators, who were hand-picked personnel and were subjected to a high rate of rotation; they were working, moreover, for short periods and with low-power sources of centimeter waves. Consequently, scientists outside the USSR were skeptical. At the same time, however, research by Soviet scientists in the USW range suggested possible biological effects of decimeter and centimeter waves (Suponitskaya et al., 1937—1938; Frenkel et al., 1937—1939; and others).

World War II (1941—1945) facilitated the development of radar techniques, which naturally led to widespread use of microwaves, i. e. superhigh frequencies (SHF) in addition to their engineering uses. Physiotherapeutic applications, dependent on the thermogenic effects of microwaves, utilizing the possibility of local irradiation at different depths from the body surface, were developed from about 1947.

The development of radio engineering created the danger of the personnel's exposure to microwaves under industrial conditions, i. e. in the manufacture of microwave generators, in the testing and operation of microwave devices.

After ten years of investigations in collaboration with the laboratory staff in the fields of occupational hygiene and the biological effects of radiofrequency electromagnetic irradiation, it is now possible to generalize the accumulated data for the range of superhigh frequencies (SHF).

This monograph does not provide a uniformly detailed treatment of its subject matter but concentrates on the occupational hygiene of personnel working with SHF sources and on protection against detrimental effects established by clinical and experimental investigations.

In our research, we used a complex of methods aimed at elucidating the biological effect of SHF from a consideration of the combination and interrelations of the nonspecific reactions which they cause.

The author hopes to make a modest contribution to the development of investigations in this comparatively new field of hygiene, based on his own experience.

Chapter I

CURRENT TRENDS OF RESEARCH IN THE FIELD OF OCCUPATIONAL HYGIENE AND THE BIOLOGICAL EFFECT OF MICROWAVES

Development of research in the USSR

As already mentioned, the earliest reports on investigations of the biological effect of decimeter microwaves appeared in the literature in 1937—1939 (Suponitskaya, 1933, 1937, 1938).

These investigations were the natural extension of those on USW, the range on which the decimeter region borders ($\lambda = 1$ m to 0.1 m). At that time investigations were conducted on a limited scale. Papers dealing mostly with the working conditions of radar operators began to appear much later (10 years) (Galanin et al., 1956; Shemyakov, 1955).

The laboratory of radio-frequency electromagnetic waves in the Occupational Health Research Institute of the Academy of Medical Sciences of the USSR was mainly concerned (from 1953) with studying the biological effects of electromagnetic waves of superhigh frequency but low intensities, which did not raise the body temperature. This approach to the new occupational-environmental hazard was prompted by the specific working conditions of personnel working with SHF energy sources in industry (construction of SHF generators) and radar technology.

Within a short time, we became convinced of the considerable biological activity of high irradiation intensities in experimental situations, and comprehensive investigations with low irradiation intensities were carried out to establish the maximum permissible irradiation intensities for personnel.

Studies of the biological effect of microwaves on human subjects and experimental animals have been pursued by the Soviet investigators in two directions: hygiene and microwave therapy. Research on the biological effect of microwaves (decimeter range) for medical purposes started back in 1938 (Suponitskaya). Continuously generated centimeter waves are now being widely used in Soviet physiotherapy.

The use of pulse microwaves is still limited. The only known paper is that by Bidenko (1959), who successfully used irradiation with 3-cm pulse waves (modulation frequencies 3,750 pulses/sec, pulse power 60 kW) for the treatment of chronic eczema and epidermophytosis, first in animals and then in man.

More thorough studies of microwaves for physiotherapeutic purposes and their actual application are conducted in the Central Institute of Resorts and Physiotherapy under the guidance of Prof. A. N. Obrosov, Associate Member of the Academy of Medical Sciences of the USSR. Without dwelling on this research trend, we should only like to point out the large number of published papers and specialized reviews in this field (Skurikhina, 1961, 1962).

The second trend — research into the detrimental biological effects of microwaves — is being pursued by hygienists, occupational pathologists, engineers, biologists and radiophysicists.

Comprehensive investigations of the working conditions of personnel working with microwave sources in industry (Gordon, 1957a, 1957b, 1958, 1960, 1961; Gordon and Belitskii, 1959; Osipov et al., 1962; Frolova, 1963) and in operation of radar stations (Spasskii, 1956; Galanin et al., 1956; Senkevich, 1959; Kalyada et al., 1959; Kulikovskaya, 1961, 1963; and others) have allowed evaluation of the hygienic conditions, including classification according to the intensity and exposure to microwaves in the case of industrial enterprises (Gordon, 1957, 1958, 1960).

The clinical picture of long-term effects of microwaves has been described by, among others, occupational pathologists in several occupational disease clinics (Kevork'yan, 1948; Merkova, 1949; Sadchikova and Orlova, 1958; Uspenskaya, 1959, 1961; Orlova, 1959; Drogichina, 1960; Drogichina and Sadchikova, 1963, 1964; Sadchikova, 1960; Belova, 1960; Sokolov and Arievich, 1960; Gur'ev, 1962; Gembitskii, 1962; Tyagin, 1962; and others). Basing their conclusions on frequent dynamic observations of subjects after long-term exposure to microwaves of nonthermogenic intensities under industrial conditions, a group of specialists headed by Drogichina differentiated three stages in the development of the disease and described its characteristic clinical syndromes (Drogichina, 1960; Drogichina, Sadchikova, 1963, 1964). The characteristics of the clinical syndrome depend on the intensity and duration of exposure to the microwaves. The syndrome caused by long-term exposure to SHF fields was described by Tyagin (1962) and others.

Considerable attention has been paid to experimental investigations of the nature of biological effects of microwaves. Research into the effect of high-intensity microwaves yielded unambiguous data on the resultant irreversible processes, characterized by heavy overheating of the body, formation of a cataract (Belova and Gordon, 1956), death of animals (Lobanova, 1960) and marked morphological changes in the organs and tissues of experimental animals (Pervushin and Triumfov, 1957; Tolgskaya, Gordon and Lobanova, 1959, 1960; Dolina, 1959; Gorodetskaya, 1962; and others). A large number of experimental investigations, especially in recent years, have been devoted to the effect of low-intensity microwaves. This preference is obviously well founded, since high-intensity microwaves obliterate the specific features of the irradiation effects, including the initial changes produced by the irradiation.

The body's reaction is quite distinct, especially in the case of long-term exposure to microwaves, and comes mainly from all divisions of the nervous system (Subbota, 1957, 1958, 1962; Tolgskaya, Gordon and Lobanova, 1957; Bychkov, 1957, 1962; Lobanova and Tolgskaya, 1960; Lobanova, 1964; Kitsovskaya, 1960, 1964; Tolgskaya and Gordon, 1960, 1964; Gordon et al., 1962, 1963; Kholodov, 1962; Zenina, 1964; Gvozdikova et al., 1963, 1964; Kholodov and Zenina, 1964; and others). Irradiation of low-intensity microwaves induced pronounced reactions in the cardiovascular system (Tyagin, 1957; Gordon, 1960, 1964; Presman and Levitina, 1962 a, b;

Gordon et al., 1962). These changes are mostly of a vagotonic nature, either reflex or related to direct effects on cerebral structures, the precise nature of which depends upon the range of microwaves (Gordon, 1960) and the localization of the irradiated area (Presman and Levitina, 1962 a, b).

Only comparatively few papers have dealt with the effect of microwave irradiation on the biochemical processes in animals and man (Nikogosyan, 1959, 1960, 1962, 1964; Syngaevskaya and Sinenko, 1959; Syngaevskaya et al., 1962; Gel'fon and Sadchikova, 1963; Smirnova and Sadchikova, 1960). They have established disturbances of protein and carbohydrate metabolism, certain enzyme activities and changes in the endocrine system. The results of long-term exposure to low-intensity microwaves suggested that the biological effect was cumulative (Gordon, 1957, 1960, 1964).

Comprehensive hygienic, clinico-physiological and experimental investigations led to tentative recommendations of permissible irradiation intensities for centimeter waves (Gordon and Presman, 1956). These estimates were made more accurate in 1957 and extended to the range of decimeter waves. In 1964, our laboratory submitted permissible norms for the millimeter range. Based on the permissible irradiation values, efficient measures for protection against the effect of microwaves were elaborated (Gordon and Presman, 1956; Presman, 1958; Belitskii and Knorre, 1960; Gordon and Eliseev, 1964).

The Soviet literature on this subject is represented by a collection of papers and reviews (Presman, 1961, 1963, 1964) which altogether comprise some 300 works.

Studies of the biological effect of microwaves outside the USSR

Investigations of the biological effect of microwaves are being conducted mainly in the USA, where this matter is regarded as important; guidance and planning of a special program of investigations have been entrusted to the U. S. Air Force Command (Knauf, 1958, 1961). Papers on the biological effect of microwaves have been published outside the USSR from 1943 on. They have been mostly concerned with the possible detrimental effect of microwaves and with their efficient use in physiotherapy.

The number of American investigations on detrimental effects of microwaves has steadily increased over the years, in proportion, evidently, to the growing power of transmitters.

At a special U. S. Air Force conference on the biological effect of microwaves (August 1960) it was pointed out that radar units for space flights, which generate fantastic power, will lead to considerable irradiation intensities for ground operators, since even parasitic leakages of microwave energy will obviously be of appreciable magnitude.

The main trends of studies of the biological effects of microwaves have included experimental investigation of the effects on various organs, functions and systems of the body, elucidation of the detrimental effect of microwave energy and elaboration of protective measures, clarification of the mechanism of biophysical processes taking place in live tissues and medical applications.

The biological effect of microwaves has been investigated mainly from the standpoint of their thermal effects. Numerous papers have thus been devoted to the theoretical and experimental investigations of temperature variations in body tissues, at different depths from the surface, due to irradiation with centimeter waves (Leden et al., 1947; Sequin and Castelain, 1947; Krusen at al., 1947; Osborne and Frederick, 1948, 1949; Worden et al., 1948; Wakim et al., 1948; Horvath et al., 1948; Murphy et al., 1950; Engel at al., 1950; Boyle, Cook and Buchanan, 1950; Cook, 1952; Schwan, 1955; Ely and Goldman, 1956; and others).

Attempts to determine the temperature of tissues at different depths by calculations based on absorbed energy (Clark, 1950; Cook, 1952) were unsuccessful, there being a discrepancy between the calculated and the experimental data.

Organs that are only scantily supplied with blood vessels are exposed to a serious danger of overheating, and therefore studies of the effects of high-intensity microwaves, launched in 1948, led to investigations of their effects on the eye (Richardson et al., 1948, 1951, 1952; Daily et al., 1950, 1952; Willians et al., 1956; Carpenter, 1959; Carpenter et al., 1960; and others). They established the threshold microwave intensities (120 — 600 mW/cm^2) for the development of cataract, immediately or a few days after the termination of irradiation.

In their attempts to clarify the mechanism of cataract formation, several investigators (Daily et al., 1951; Carpenter et al., 1960; and others) discovered that the sequence of development of certain biochemical changes in the eye lens upon exposure to microwave irradiation was different from the sequence observed in the changes in cataracts caused, for instance, by ionizing radiation. The prolonged latent period between irradiation and cataract formation, as well as certain specific features of the biochemical processes in the eye lens, led some authors to suggest a nonthermic nature of the ocular effect of microwaves.

Nonthermic effects of microwaves were similarly suggested for microwave irradiation of testes (Gunn, Gould and Anderson, 1961).

Fewer papers have dealt with the effect of microwaves on the nervous system, and these studies have mostly been concerned with high irradiation intensities (Oldendorf, 1949; Austin and Horwart, 1954; Baldwin et al., 1960; Fleming et al., 1961). The histological changes of the cerebral matter were very pronounced, indicating considerable thermal effects.

The second trend has been concerned with the detrimental effect of microwaves on the human organism and the assessment of hygiene in occupations involving microwave irradiation. The scope of these investigations has been limited mainly to Air Force and Navy personnel operating radar units. Mass investigations of the health of such personnel were carried out in 1956 — 1958 (Brody, 1956; Barron, Love and Baraff, 1956 a, b, 1958). These investigations revealed several functional disturbances in the nervous system, certain changes in the peripheral blood system and in lenticular opacity. We were unable to find in the available literature a clear assessment of hygiene in the working conditions involved and occupational-pathological syndromology of microwave irradiation.

Research on the permissible norms of irradiation intensities for personnel working with microwave sources was carried out in 1957. The conclusions were based on experimental and calculated data, using the damaging thermal effect of microwaves as the criterion of judgment. In consequence the considerable irradiation intensities adopted by the USA as the permissible norms were established.

Technical protection against irradiation is based on reflection or absorption of the microwave energy, in addition to various preventive and administrative measures (Vosburgh, 1956; Egan, 1957; Ch. D. La Fond, Gettings, 1961; Mumford, 1961).

Several papers, including some reviews, have followed the third trend, i.e., elucidation of the mechanism of the biological effect of microwaves, especially the primary biophysical processes occurring in the tissues of living organisms. They included investigations of the electrical properties of tissues. in SHF electromagnetic fields and the mechanism of microwave absorption by different tissues in the body of animals (Roberts and Cook, 1952; Schwan and Piersol, 1954; Hartmuth, 1954; Schwan, 1957, 1958; and others).

Reflection of microwaves from an animal's body surface and their propagation and absorption in the tissues depend upon the latter's electrical properties (dielectric constant and electric loss factor) and the frequency range used (England, 1950; Cook, 1951; Schwan and Li, 1953; Fleming et al., 1961). Absorption of microwave energy in tissues may involve transformation of electromagnetic energy into thermal energy by processes involving changes in ionic conductivity and relaxation of excited states of the dipoles, in water. The dipole processes begin to play the dominant role in energy absorption at shorter wavelengths. Resonance absorption of microwaves by protein molecules has been suggested by several investigators (Dryden and Jackson, 1952; Roberts and Cook, 1948; Kalant, 1959; Vogelhut, 1960; Prausnitz et al., 1961).

Microwave diathermy (the fourth trend in the use of radiowaves) was introduced by American medical investigators around 1947, but neither the physiologically harmless irradiation dose nor the microwave frequency had yet been definitely established. Diathermy is performed with frequencies between 2,460 and 3,000 mc, but according to Schwan, the optimum frequency for medical diathermy should be lower.

On a smaller scale, investigations of the biological effect of microwaves for medical purposes were conducted in France and the Netherlands (until 1950) and are being continued in the United Kingdom, Italy and the Federal German Republic. Investigations of microwaves for physiotherapeutic purposes have been based on continuous radiation. Over 20 organizations in the USA are investigating the biological effect of microwaves, including universities, institutes, laboratories, military institutions and private companies.

A group of papers have been devoted to measurements of irradiation intensity and the instruments used for this purpose.

The above does not exhaust the entire range of investigated aspects of the biological effect of microwaves and all the organizations conducting research on the subjects. Over the last 3—5 years, papers on the biological effect of microwaves have appeared in several socialist countries, including Czechoslovakia, Bulgaria and Poland.

Thus, the great majority of investigators engaged in research of the biological effect of microwaves continue to use high irradiation intensities. They naturally remain concerned with the thermal effect of microwaves.

Nevertheless, more attention has recently been paid to the biological effect of low irradiation intensities, as is attested to by the agenda of the third and the fourth world congresses on radioelectronics in medicine. At the third congress (London, 1960), the effect of low-intensity microwaves was discussed in only one paper out of ten (USSR), but at the fourth congress in 1961 (New York) ten out of twenty papers, including one from the USSR, dealt with the nonthermic effect of microwaves.

In summarizing the status of Soviet and other investigations of the biological effect of microwaves, one must emphasize certain basic aspects. The Soviet investigations, from 1953 on, provided data on the working conditions of personnel and on the biological effect of microwaves on the organism. The period 1957—1965 was marked by research into permissible irradiation levels and means of protection, accompanied by deeper investigations of the biological effects at low intensity of irradiation and by a considerable expansion of the investigated microwave (millimeter, decimeter) and longer wavelength (ultrashort, short and medium ranges.

Research outside the USSR, beginning approximately in 1940—1943, has been largely concerned with the effect of high irradiation intensities on the organism. Investigators' attention to hygiene has concentrated on the working conditions of radar operators in military units. The official norms for this kind of personnel are based on the thermal effect of microwaves, and they are one order of magnitude higher than the maximum permissible norm for short-term exposure (1 mW/cm^2), adopted in the USSR. Some attention has been paid to investigations of the mechanism of primary biophysical processes induced by microwave irradiation.

In contrast to the comprehensive (clinico-hygienic and experimental) Soviet research, analogous American investigations have been concerned with different separate aspects of the subject, conducted in different scientific research institutions. The American scientists have been occupied with the high microwave irradiation intensities experienced by operators of radar units in connection with the development of missile techniques, and they seem to be little concerned with industry manufacturing radar equipment.

Our experience has shown that the working conditions in industry manufacturing SHF devices strongly affect the degree of wave irradiation of the personnel.

The main purpose of our work is to investigate the nature of the biological effect of microwaves and the degree of their detrimental effect and to assess the conditions of industrial personnel working with microwave sources.

Chapter II

PHYSICAL CHARACTERISTICS OF ELECTROMAGNETIC WAVES OF RADIO FREQUENCIES AND THEIR MEASUREMENT

Fundamental physical concepts related to radiofrequency electromagnetic waves and their applications

Conventionally, radiowaves occupy the region of the electromagnetic spectrum of wavelengths from 3 km and longer down to 1 mm.

If the radiowaves are arranged in the electromagnetic spectrum in the order of diminishing wavelengths (or, correspondingly, increasing frequencies), they are divided conventionally into long, medium, short, ultrashort and microwaves, of correspondingly high (HF), ultrahigh (UHF) and superhigh (SHF) frequencies (Table 1).

We shall make a detailed examination of the range of microwaves — superhigh frequencies (SHF) located between infrared radiation and UHF radiowaves. The microwaves possess more marked optical properties and are more heavily absorbed by biological media in comparison to radiowaves in the long-wave range.

TABLE 1. Electromagnetic waves in the range of radio frequencies

	Radiowaves						
	long	medium	short	ultrashort	microwaves		
					decimeters	centimeters	millimeters
Wavelength	3,000 m	100 m	100 — 10 m	10 — 1 m	1 m — 10 cm	10 — 1 cm	1 cm — 1 mm
Frequency	100 kc	3 Mc	3 — 30 Mc	30 — 300 Mc	300 — 3,000 Mc	3,000 — 30,000 Mc	30,000 — 300,000 Mc
	High frequency (HF)			Ultrahigh frequency (UHF)	Superhigh frequency (SHF)		
Industrial, scientific, and technical applications of radiowaves	Thermal treatment of metals (hardening, smelting, soldering, etc.) Thermal processing of dielectrics (drying of wood, foundry cores, heating of plastics, welding of plastics, glueing of wood articles, etc.) Radiocommunications Physiotherapy			Radio communications and TV Physiotherapy	Radiolocation Radionavigation Radio relay systems Radioastronomy Radiometeorology Radiospectroscopy Nuclear physics Radiocommunications Physiotherapy, etc.		

Radiowaves comprise components of interrelated time-variable electric and magnetic fields, and the energy carried by a radiowave is divided evenly between the electric and the magnetic field components. Similar to light, the propagation velocity of radiowaves depends upon the propagation medium and is approximately $3 \cdot 10^8$ m/sec in free space. The relationship between the propagation velocity c, wavelength λ and frequency f is given by the expression

$$\lambda = \frac{c}{f}$$

Reflection, refraction and diffraction of radiowaves. Radiowaves are reflected from any inhomogeneity in the propagation medium. The amplitude and phase of the reflected wave depend upon the size and nature of such an inhomogeneity.

Radiowaves are largely reflected from metallic objects, ground and water surfaces, buildings, etc.; they are fully reflected from large electrically conducting surfaces, but only partially from dielectric surfaces. SHF energy is partially absorbed by dielectrics and semiconductors.

Radiowaves are reflected in the same manner as light, i. e., the wave changes its direction of propagation while crossing (at an oblique angle) the interface of two media with different velocities of propagation. This change in the direction of propagation occurs because the part of the wave front that is the first to reach the interface proceeds to move faster or more slowly than the part of the front reaching the interface later on. As a result, the wave front changes its direction.

In cases where the dimensions of the irradiated object are of the same order of magnitude as the wavelength of the radiowave, diffraction occurs, i. e. the radiowave passes around the obstacle and proceeds in its propagation path with scarcely any reflection.

These properties of microwaves call for a definite approach in the assessment of the hygiene of working conditions and in devising means of protection from their deleterious effects.

As shown in Table 1, sources of SHF energy (microwaves) are widely used in various fields of science and technology.

Radionavigation and radiodirection finding are used for navigating ships and aircraft by determining their position with respect to radio stations acting as beacons. Radiometeorology includes observations of radiosondes and radiolocation of rain and storm clouds for weather forecasting.

In radioastronomy signals are received by means of special antennae of large dimensions (radiotelescopes) for the study of radio emission of celestial bodies. Radioastronomy studies solar radio-frequency radiations with the aim of forecasting disturbances in the terrestrial ionosphere. A characteristic feature of these systems is the absence of transmitting devices and the use of receivers of superhigh sensitivity (up to 10^{-18} watt).

Radiotelemetry is the gathering, transmission and processing of information on physical processes that are inaccessible to direct observation and control, for instance, information from spaceships, man-made Earth satellites, rockets and in medical investigations. Radiocontrol comprises methods for the transmission and processing of control signals, for control of various objects (ground-to-air, air-to-air, ballistic missiles, etc.). Radio relay systems are used for long-distance telephony and television by means of automatically controlled relay stations. Radiospectroscopy is the study of resonance absorption of radiowaves in various substances for determination of the latter's composition and properties. It is used for research in molecular, atomic and nuclear physics.

Radar equipment occupies a fairly important place among the variety of uses of SHF apparatus. From the standpoint of health, the most important studies are those of the working conditions in the manufacture and operation of radar equipment, as well as introduction of means for protection against possible SHF radiations.

Fundamental principles and units of measurement of SHF electromagnetic fields. Measuring devices

In practical hygiene, the energy of any region of the electromagnetic spectrum is usually characterized by an irradiation intensity. Irradiation intensities in the range of radio frequencies are expressed in a variety of units.

In the case of meter and longer waves, the irradiation intensity is assessed from the sum of the electric field strength (E) and magnetic field intensity (H) measured separately with a voltmeter and an amperometer, respectively. This is because in work with sources of long, medium, short and even ultrashort waves the point of measurement is usually within the induction zone, i.e., at a distance from the radiation source smaller than one-sixth of a wavelength, and within the induction zone the electric and magnetic field components are not quantitatively correlated.

In the case of decimeter, centimeter and millimeter SHF waves, the point of measurement is as a rule within the wave zone, i.e., at distances considerably exceeding the wavelength. The electromagnetic field in the wave zone is formed and spreads in the form of a traveling wave, and in this case, the electric and the magnetic field components are rigidly interrelated [according to the Maxwell relations]. Therefore, the irradiation intensity in the SHF range is assessed from the total flux density of radiated power-PFD* expressed in W/cm^2, or mW/cm^2, or $\mu W/cm^2$.

The most commonly used units for PFD in practical hygiene are mW/cm^2 or $\mu W/cm^2$.

Occasionally, it may be feasible to assess irradiation intensity in uniform units of energy density expressed as erg/cm^3, for convenient comparison of irradiation conditions in different radio-frequency bands in the wave and induction zones.

Thus, for the case of wave zone the energy density is determined by the formula

$$W, erg/cm^3 = \frac{P(W/cm^2)}{C(cm/sec)},$$

where W and P are, respectively, the energy density and power flux and C is the propagation velocity of the electromagnetic vibrations.

* PFD (power flux density) of SHF vibrations is defined as the energy of SHF vibrations passing per second through unit surface perpendicular to the direction of the propagation of energy.

For the case of the induction zone, where the electric and the magnetic components are independently variable, it is possible to use the following expression for the energy density:

$$W(\text{erg/cm}^3) = W_E + W_H = \frac{\epsilon E^2}{2} + \frac{mH^2}{2},$$

where W_E is the energy density of the electric field;
W_H — the energy density of the magnetic field;
E — the strength of the electric field component, V/m;
H — the intensity of the magnetic field component, amp/m;
ϵ — the dielectric constant;
m — the magnetic permeability.

If the measurements are performed under conditions making possible energy reflection, the PFD is determined as the sum of incident and reflected energy measured with an instrument in two directions (0°, +180°) for the HF and UHF range, and in four directions (0°, +90°, +180°, +270°) for the SHF range in the case of multiple reflection.

The principle of the measurement of the power flux density is as follows. The SHF power is picked up by a receiving antenna for a suitable range of wavelengths. The transducer responding to the power of SHF vibrations is usually a thermistor included in a d. c. circuit, in one arm of a bridge scheme. The thermistor is included in a waveguide or a coaxial line due to the high-frequency load. A variable calibrated attenuator is included between the receiving antenna and the thermistor head. The attenuator is adjusted in such a position that the instrument reading in the bridge diagonal will always be the same, corresponding to a definite power dissipated by the thermistor. The measurements may also be based on the degree of bridge unbalance (using the calibrated scale of the instrument).

The reading obtained by means of the attenuator, expressed by the attenuation factor multiplied by the standard value of the thermistor bridge power, yields the value of power received by the antenna:

$$P_{in} = K_a \cdot P_T,$$

where K_a is the attenuation factor of the attenuator scale;
P_T — the standard value of power dissipated by the thermistor; and
P_{in} — the power received by the antenna.

Determination of the power flux density requires knowledge of the effective surface of the measuring antenna, which is determined by the formula

$$S_{eff} = \frac{G\lambda^2}{4\pi},$$

where G is the antenna gain factor and λ is the wavelength in free space.

The power flux density P, in mW/cm², is then determined by the formula

$$P = \frac{P_{in}}{S_{eff}} = \frac{P_T \cdot K_a}{S_{eff}}.$$

If the attenuation in the connecting cable or the coaxial-waveguide adapters is to be taken into account, they must be included in the total attenuation, i. e.,

$$K_{tot} = K_a \cdot K_c \cdot K_w,$$

where K_c and K_w are the respective factors for attenuations in the cable and in tbe coaxial-waveguide adapter.

In this case, the power flux density is

$$P = \frac{P_{in}}{S_{eff}} = \frac{P_T \cdot K_a \cdot K_c \cdot K_w}{S_{eff}}$$

In 1952—1953, the laboratory of our institute, working in collaboration with a radio-engineering factory, designed and constructed for the first time an instrument for PFD measurements in the range of 10-cm waves, designated as IPP-10. This was the first stage in the design of the measuring instrument for hygienic investigations of industrial hygiene.

The IPP-10 PFD meter is based on the principle of absorption of the entire power arriving at the effective surface of a horn antenna. A high-frequency load is carried by a thermistor of resistance $R \simeq 200$ ohm, subjected to pulses of irradiation. The dimensions of the thermistor are larger than is usual in order to minimize overheating.

The thermistor is a semiconductor, the resistance of which is very sensitive to temperature changes and consequently also to variation of absorbed power. This property of the thermistor was used for measuring the average high-frequency power of the irradiation by comparing it with the power of a direct current, producing the same thermal effect in the thermistor.

The second stage in the use of measuring equipment for hygienic assessment of irradiation intensities in an SHF field was implemented in 1956-1957. Investigations which enabled us to recommend the maximum permissible irradiation intensities in the range of centimeter and decimeter waves necessitated design of laboratory instruments for PFD measurements. For this purpose we used several commercial meters of low power equipped with antennae of known effective surface area, suited to absorption of the required wavelengths, and connected to the meter input through an attenuator.

In our investigations, the instrument 31 IM ("radar tester") was widely used for the wave range 3.1—3.45 cm, while the low-power meter IMM-6 with a set of calibrated antennas was used for the range 10—100 cm.

The basic diagram of the measurements is shown in Figure 1.

The low-power meter was connected to the standard antenna by means of a coaxial-waveguide adapter with a cable, the attenuation of which is known beforehand. The PFD is determined by the formula already known, which requires knowledge of the effective surface of the measuring antenna.

However, such laboratory measurements are insufficient to fix norms of permissible irradiation, since these should be assessed in the natural conditions of personnel working SHF generators. In such conditions protective measures may be recommended, if necessary.

The third and final stage in the development of measuring equipment was the designing of a new instrument satisfying the requirements of assessment of irradiation intensity for personnel exposed in the SHF range.

Such an instrument designated PO-1 ("medik-1") was developed in 1960.

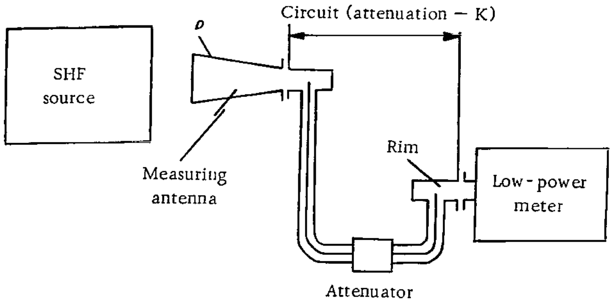

FIGURE 1. Basic diagram for measurements of power flux density

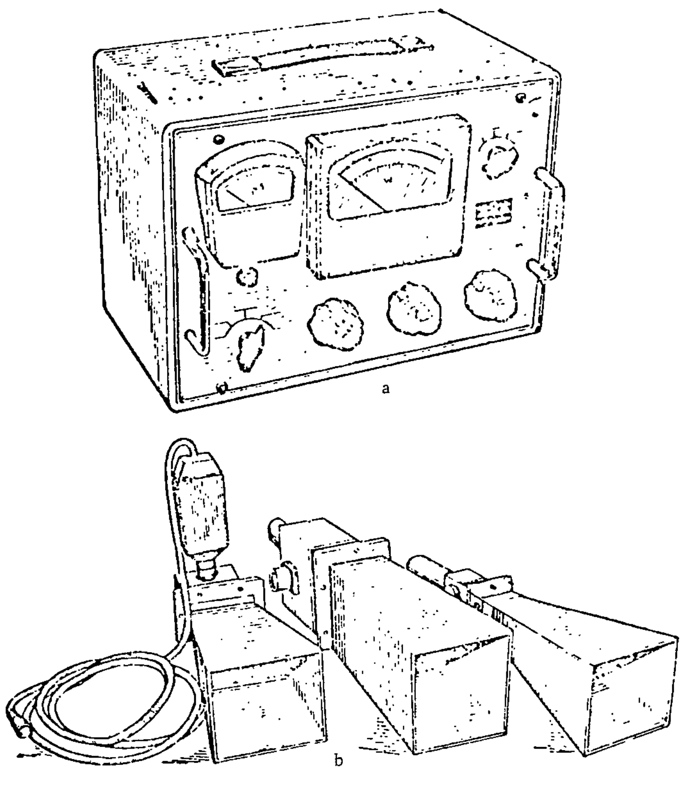

FIGURE 2. PO-1 apparatus:

a — low-power meter; b — thermistor head and horn antennas.

The PO-1 type PFD meter (Figure 2) consists of equipment suitable for measurement of radiation intensities from various radio-engineering devices in the laboratory, shop and field, in the wave range experienced in such working conditions (i.e., decimeter—millimeter waves).

Chapter III

CHARACTERIZATION OF THE HYGIENE CONDITIONS OF PERSONNEL WORKING WITH SHF SOURCES

Characterization of the hygiene conditions

Occupational hygiene in conditions of work with sources of SHF electromagnetic waves (microwaves) has been studied by Galanin et al., Senkevich, Kalyada et al., and Kulikovskaya, who described the work environment of radar operators.

Thus, Kalyada et al. (1959) measured considerable PFD (stray radiations of up to hundreds of $\mu W/cm^2$ with covered SHF blocks and up to thousands of $\mu W/cm^2$ with uncovered blocks) in radio rooms during the tuning and adjustment of radar transceivers. PFD values may reach up to several mW/cm^2 in certain open areas on board ships depending on the location and nature of the radiating devices. Irradiation may sometimes reach tens of $\mu W/cm^2$ on coastlines and piers.

Kulikovskaya (1963) examined the irradiation intensities encountered by ship crews at different distances from the antenna, in the direction of maximum radiation. She demonstrated that PFD may vary from 4 to 460 $\mu W/cm^2$ on the decks and bridges of ships and that the most unfavorable conditions occur in cases when the radar antenna is mounted on a mast 1.2 — 2.5 m tall. Architectural features of the ship and the location of radar antennas (shading by stacks, superstructures, etc.) are important in this respect.

Hygiene investigations in radar operation were carried out on civilian airfields (Loshak, 1963).

Only two Soviet papers have furnished hygiene data directly related to the industry engaged in the manufacture of SHF devices (Osipov et al., 1962; Frolova, 1963). Osipov et al. demonstrated that the personnel employed in the tuning and testing of radio technical devices by means of low-power generators (30 — 100 mW) in the laboratory may become exposed to local irradiation (mainly of the hands) of intensities up to 20 — 30 $\mu W/cm^2$, sometimes increasing to several hundreds $\mu W/cm^2$ in the case of direct radiation. Frolova (1963) mentioned limits of PFD from 0.005 to 30 mW/cm^2 to which the workers may become exposed, continuously or periodically, in her description of the working conditions and state of health of 172 personnel, in the section of a factory dealing with sources of centimeter and decimeter waves. Such wide ranges of PFD were due to the absence of proper means of protection and to inappropriate arrangement of the radiating devices.

Several authors outside the USSR (Barron et al., 1956; Sercl et al., 1961) have furnished hygiene assessments for work with SHF energy sources. Barron et al. differentiated two zones with respect to PFD in radar operation, and they considered clinical data in relation to irradiation intensity (0.0131 W/cm^2 and 0.0039 W/cm^2). Sercl et al. assessed irradiation levels according to the classifications suggested by ourselves, i.e., by irradiation intensity and duration (Gordon, 1957, 1958, 1959, 1960).

The authors investigated the conditions of work and health of the following two groups of workers: firstly, personnel working in radar cabins (in the field) and exposed to systematic irradiation of low intensity; secondly, personnel of research departments irradiated periodically with high intensities. According to the authors, the second group works under worse conditions.

Certain non-Soviet investigators provide data indicating considerable PFD in the vicinity of radiating antenna (Tolles and Horvath, 1956; Mumford, 1961), without describing the hygiene conditions of personnel working with SHF energy sources.

Mumford gave data making it possible to determine distances (along the beam), for different types of radar, at which PFD is 10 mW/cm^2. Allen (1958) proposed a nomogram for calculating the mean PFD in the direction of the main bearing of radar antenna (for a parabolic reflector). These data, however, cannot solve the problem of PFD to which the personnel may be exposed in every specific case, and are certainly quite inapplicable to assessment of work with SHF sources indoors. Hence, the data on the permissible irradiation of personnel working with microwaves refer mainly to radar operators.

Data reported by various authors (Osipov et al., Frolova) on conditions in industrial enterprises manufacturing SHF apparatus refer only to some sections of the enterprises and do not provide an idea of the hygiene conditions of the workers, engineers and technicians employed in the manufacture, adjustment and testing of SHF apparatus.

Our data assess the conditions of personnel employed in the adjustment, tuning and testing of various types of radar generator tubes, units and entire apparatus in the SHF range according to the following criteria:

1) description of the main sources of SHF radiation into the work area for different technological processes;

2) assessment of the work conditions in relation to irradiation intensity and duration in different SHF ranges;

3) clinico-hygiene comparisons of the work conditions and health of personnel dealing with SHF energy sources.

The possible sources of radiation (from radar units) of SHF energy penetrating to the worksites, include the radiating system, the cathode leads of the magnetron, the waveguide-coaxial adapters, flange couplings, structural apertures and slots in the waveguide tract components.

The important indexes of conditions of hygiene for personnel working in the vicinity of a radiation source include the generator power, the width and tilt of radiation pattern of the antenna system, the working range of frequencies and the operation pattern (sectoral or circular scanning) and the presence of reflecting surfaces.

We differentiated six groups of operations, according to the technological process and work conditions.

Group I includes adjustment, tuning and testing of complete radar units in the finishing shops of factories and repair workshops. The principal radiation sources in a shop are the antenna systems. Irradiation intensities at worksites in these shops reach 10 mW/cm^2 and higher.

Personnel working under especially unfavorable conditions are the fitters of antenna systems who, while assembling antennae may be irradiated by nearby working radar units (PFD up to 10 mW/cm^2 and higher). Bridge crane operators working in the shop are likewise exposed to unfavorable conditions. They may become exposed to irradiation of considerable intensities (up to 0.5 — 4 mW/cm^2) in the course of their working day, even though separated from the radiating antenna by large distances (up to 30 — 35 m). The entire shop personnel may be irradiated when an antenna is rotating or scanning. The personnel engaged on repairs of radar apparatus in workshops are exposed to high irradiation intensities (1 mW/cm^2 and higher), and various SHF ranges, due to the considerable number of radar units undergoing repairs at the same time and the comparatively small work area. As a rule, the testing, adjustment and tuning of complete radar units operating on millimeter and decimeter waves are performed outside the shop, and these work conditions are described in group II.

Group II — adjustment, tuning and testing of complete radar units in testing grounds.

Work in test grounds precludes most reflection of waves and considerably reduces the number of personnel exposed to irradiation, since the majority are in cabins or indoors.

The work conditions of personnel engaged in testing of complete radar units in testing grounds depend on the latter's area and the number of simultaneously operating radar units. As a rule, testing grounds attached to the factory are small and may be used for the testing of several radar units at the same time; this may involve the possible summation of PFD and mutual irradiation of worksites, with intensities up to 500 $\mu W/cm^2$ and higher.

Moreover, the proximity of factory testing grounds to its workshops (up to 300 — 500 m) causes irradiation of personnel not directly concerned with operation of the radiation sources. The irradiation intensities are much lower in the case of personnel working in testing grounds outside the municipal boundaries.

In the adjustment and testing of complete radar units in the factory finishing shops and in testing grounds, the limits of irradiation time and intensity depend on the technical parameters of the various types of radar and the specifications which they must satisfy.

Group III — work conditions involved in the adjustment, tuning and testing of separate SHF assemblies, blocks and devices.

This group involves the following three main processes:

1) testing of antenna-waveguide tract components for electric strength;
2) testing and pre-aging of generator tubes;
3) testing of generator units.

The possible radiation sources are cathode leads of the magnetron, insertion sites of plungers for the tuning of grid and anode circuits of generators assembled with metal-ceramic tubes, rotating adapters, waveguide-coaxial adapters, flange couplings, arresters for the switching of antenna from reception to transmission, phase inverters, bullet transformers, antenna equivalents in the case of incomplete energy absorption, etc.

PFD remains mostly within tens of $\mu W/cm^2$ during the testing and pre-aging of generator tubes and exciters from low-power generators, and in the case of generator units operating at normal power levels, but it may reach thousands of $\mu W/cm^2$ in the testing of radiators operating at high power levels.

Group IV — work conditions with SHF sources in scientific research institutes.

In the course of experimental construction and testing of models and samples of radar units in scientific research institutes, SHF fields may affect personnel working in laboratories involved with transmitting and antenna devices and testing of the complete assembled radar units, and also specialists in other specialized laboratories. The antenna tests of assembled radar units are performed under conditions approximating the actual work conditions, and PFD may reach thousands of $\mu W/cm^2$ at the site of work. The irradiation intensities are higher in experimental work on models of transmitting devices than in work on complete radar units. The work with radiation sources in scientific research institutes is performed periodically at large intervals (weeks and months).

Group V — work conditions of civilian radar operators.

The conditions, for instance, at a flying-testing airfield are characterized by considerable irradiation intensities (hundreds and thousands of $\mu W/cm^2$) and depend upon the power of the transmitting devices, the height of antenna systems, direction of antenna radiation and distance from the source of SHF energy. The irradiation intensities are considerably lower in the case of operators in transceiving radar cabins.

Under such conditions, radar operators may be exposed to continuous irradiation, while the airfield personnel may be exposed periodically, depending upon the operation pattern of the radar unit.

Group VI — work conditions of SHF operators in certain branches of the national economy, for instance, meteorological stations, radio-relay communications systems, physiotherapy clinics.

Irradiation intensities are not high (a few $\mu W/cm^2$) in instrument rooms of radio-relay communications systems, but they may reach up to 400 — 2,000 $\mu W/cm^2$ at meteorological stations and especially in physiotherapy clinics.

Other industrial environmental factors that require attention are the meteorological conditions and the noise intensity level. The most unfavorable conditions occur in the electronic industry, where the air temperature in some workshops may reach 25°C during the hot part of the year, air humidity 29 — 34%, and noise intensity level 82 — 99 db. Personnel working in the testing grounds and operators in radar cabins are exposed to wide climatic fluctuations.

Assessing the hygiene of work conditions in relation to SHF intensity, duration and range requires norms of all relevant factors, elaboration of means of protection, and assessment of clinical data from the standpoint of occupational pathology.

All occupations involving irradiation can be usefully divided into the following three groups, according to the intensity and exposure:

first group — periodic exposure to high irradiation intensities (0.1 — 10 mW/cm^2 and higher);

second group — periodic exposure to low irradiation intensities (0.01 — 0.1 mW/cm^2);

third group — regular exposure to low irradiation intensities.

Clinico-hygienic comparisons of the work conditions and the state of health of personnel working with SHF sources

We have examined clinical aspects of long-term exposure to SHF fields (microwaves) insofar as they reflect the conditions of work and health of personnel working with microwave sources.

Investigations of the detrimental long-term effects of microwaves on human subjects from the occupational-pathological standpoint commenced in the 1940s.

The first clinical examinations of personnel working with microwave sources (centimeter waves) yielded negative results. Thus, Daily (1943), who examined periodically a group of 45 personnel working with radar in a laboratory for periods ranging from 2 months to 9 years, was unable to observe effects due to exposure to the microwaves. Similar conclusions were suggested by the investigation carried out by Lidman and Cohn (1945). The latter results could be attributed to the laboratory conditions, in which low powers of microwave sources and unsystematic irradiation of the personnel would prevail. In addition to this, the search for specific detrimental effects of microwaves, in accord with contemporary notions, and the comparatively small number of subjects observed may have contributed to to a failure to observe effects. Nevertheless, in 1947—1953 certain investigators, such as Richardson et al. (1948), Salisbury et al. (1949), Oldendorf (1949), Brody (1953), Hines and Randall (1952) and Hirsch and Parker (1952), reached the conclusion that microwaves had a detrimental effect and that the personnel working with microwave irradiation sources required protection; in some cases this conclusion was prompted by broad experimental investigations of the effect of microwaves, in others by observations of isolated cases of ocular injuries in human subjects.

The first clinical investigations outside the USSR of a comparatively large group of subjects (226 aircraft industry workers who could conceivably be exposed to centimeter waves) appeared only in 1956 (Barron et al.). Assessment of the conditions of work with microwave sources revealed that the irradiation conditions for the 226 subjects were nonuniform, and exposure ranged from occasional to regular irradiation up to 4 hr daily. The maximum period of employment with exposure to microwaves was 13 years, and the age range was from 20 to 50. All observations on the test group were compared in parallel to those on a control group (88 subjects) and were repeated several times. The few subjective complaints of personnel were limited to feelings of thermal sensations while in the vicinity of antennas of radar units operating in the 3-cm range.

The authors did not specify the PFD at worksites, but the subjects' subjective reports suggest very high irradiation intensities, sometimes much above 10 mW/cm^2.

The data reported by the authors as a result of detailed examination included changes in the peripheral blood — an increase of WBC in 58% of the subjects and an increase in the count of polymorphonuclear cells in 35% of the subjects.

A second investigation was carried out later by Czech scientists (Sercl et al., 1961), who investigated two small groups of workers (36 persons altogether), exposed either continuously to low-intensity irradiation or periodically to high-intensity irradiation by centimeter waves. They investigated the functional state of the autonomic and the central nervous system (pulse, blood pressure, Bourdon tests as modified by Ivanov-Smolenskii, latent period of reaction to light, etc.) before and after work.

The results of this investigation revealed some reactions (fatigability, somnolence, headache, EEG changes), especially pronounced in the group of workers periodically exposed to irradiation of intensity 1,000 $\mu W/cm^2$ and higher. The authors did not report any organic lesions of the nervous system. Similar data were obtained by Klimkova-Deutschova (1957) on a group of 72 workers. Subsequently (1963), Klimkova-Deutschova and Roth described the following three stages of neurological changes with long-term exposure to centimeter waves:

the first stage — distinguished by the neurasthenic syndrome with functional symptoms of predominant autonomic disturbances;

the second stage (more common) — distinguished by mild organic lesions of the nervous system;

the third stage (rare) — distinguished by organic lesions of the nervous system bordering on distinct encephalopathies.

We have not been able to trace any other work done outside the USSR related to clinical examination of large groups of personnel working with microwave sources. Individual cases of ocular damage and lethal cases, unconvincingly attributed to the effect of microwaves, have been reported.

Considerably wider clinical examinations of the health of personnel working with SHF sources have been performed by Soviet investigators. These investigations can be divided into two groups of which the first is closely similar to research done outside the USSR. Papers in this first group deal with clinico-physiological observations of radar operators, as affected in particular by conditions in the cabins and work premises. Thus, Shemyakov (1955) and others observed several kinds of disturbances which included, among others, functional changes in the central nervous and cardiovascular systems, trophic disturbances, ocular fatigue, small changes in the peripheral blood (mild leukopenia, mild lymphocytosis, eosinopenia, small rise of RBC and hemoglobin). Yet, there are not sufficient grounds for attributing the above changes solely to the effect of the SHF field, and the majority of authors have pointed out an entire complex of factors (noise, meteorological conditions, high CO_2 concentrations, ocular strain, attention stress, uncomfortable posture, etc.) which affect the working conditions of radar operators.

Few investigators have described symptoms due to SHF fields at the site of work and only one paper mentions that the operators working for 1 — 2 hr on radar units suffered temporary bradycardia and sometimes hypotension. It is, however, difficult to determine the irradiation intensity on a subject, in such conditions.

The second group of investigations deals with the health of subjects exposed for prolonged periods under a variety of conditions to microwaves, mainly of the centimeter range (Uspenskaya, 1959, 1961; Gembitskii, 1962; Tyagin, 1962; Gur'ev, 1962; Treskunova and Slizkii, 1962; and others).

On the whole, the authors arrived at similar conclusions; their investigations reveal functional disturbances in the nervous and cardiovascular systems, certain changes in the peripheral blood system and the endocrine glands and lenticular opacity.

A group of clinical investigators working in the Occupational Health Research Institute of the Academy of Medical Sciences of the USSR has provided detailed descriptions of the clinical syndrome produced by long-term exposure to microwaves (Kevork'yan and Merkova, 1948), and from 1953 a group of specialists headed by Drogichina and including Sadchikova, Orlova, Belova, Sokolov, Chulina, Gel'fon, Khmara, Glotova and Smirnova joined the research effort. The clinical studies of long-term exposure to microwaves were based on investigations over ten years of more than 1,000 subjects, among whom 100 were kept under dynamic observation of the institute for nine years. The control group also included 100 subjects.

To a certain extent, this large group of subjects could be said to be uniform since their age was mostly not above 40, and the length of employment involving exposure to microwaves was mostly over 5 years.

The long-term exposure to microwaves produced functional disturbances in the nervous system of varying strength (Sadchikova, 1960, 1964), the most characteristic of which is the asthenic state syndrome occurring against a background of angiodystonia. There may be transient changes in the peripheral blood, and also certain changes in biochemical indexes (Gel'fon and Sadchikova, 1960; Gel'fon, 1964) and endocrinal disturbances (Smirnova and Sadchikova, 1960).

The most characteristic effect of microwaves on the autonomic innervation is the trend towards predominance of the parasympathetic contact of the cardiovascular system (Orlova, 1959, 1960; Konchalovskaya, Khmara and Glotova, 1964). This includes bradycardia and hypotension, as well as changes in the ECG indexes (sinus arrhythmia, extrasystole, changes in the intraventricular and intraatrial conduction, diminished amplitude of ECG deflections, etc.) due to disturbances in extracardial factors.

Reversible peripheral blood changes, studied by Sokolov et al. on the same group of subjects (1962, 1964), were characterized by some instability of white blood indexes and manifested themselves in particular by a tendency to cytopenias, including mild leukopenia, thrombocytopenia, as well as relative lymphocytosis and reticulocytosis. Microwaves are evidently not a marked occupational-pathological hazard with respect to the blood system.

The clinico - physiological and biochemical investigations permitted deeper studies of the functional changes of central and autonomic nervous reactions in patients suffering from long-term exposure to centimeter waves. For instance, there were uniform changes in the bioelectric cerebral activity of such patients, manifested by diffuse slow activity and bilaterally synchronous trains of high-voltage theta and delta waves (Ginzburg, 1964). Investigations of the cutaneogalvanic reflex (Ginzburg, 1964) revealed autonomic instability and enhanced excitability of the central divisions of the autonomic nervous system. The strength of EEG changes was correlated with that of other clinical symptoms produced by long-term exposure to microwaves, the most pronounced changes occurring in cases of diencephalic insufficiency. Investigations with radioactive iodine (I^{131}) revealed increased thyroid activity, without clinical signs of thyrotoxicosis. The patients' blood exhibited an increase in histamine, an increased concentration of total protein due to changes in the globulin fractions in the blood serum and a decrease of the albumin/globulin ratio.

Under especially detrimental work conditions, microwaves may cause ocular injuries (lenticular opacity), progressive with the course of time.

Marked forms of cataract were diagnosed by Belova (1960) in a few cases. In mass investigations, however, the number of such cases was only a little higher than that in the control group.

Our dynamic observations, conducted in collaboration with a group of clinicians from 1953 on, have revealed the relationship between the disease and the conditions of work with microwave sources.

The developmental dynamics of the clinical syndrome produced by long-term exposure to microwaves was divided by Drogichina et al. (1962, 1964) into the following three stages: initial, moderate and pronounced.

The first two stages are characterized by the asthenic state syndrome combined with vascular changes normally under vagotonic control. In these stages, the process is reversible, and the subject's health can be restored by suitable treatment and by cessation of work with SHF sources. In their pronounced stages, the neurocirculatory disturbances are characterized by sharp fluctuations of the vascular tone, paroxysms and dominance of the sympathetic nervous system. The clinical picture of this stage often includes diencephalic syndrome with marked EEG changes. The pathological process becomes more persistent in this stage and may impair the subject's working ability.

The period preceding the appearance of clinical symptoms produces several physiological changes that were observed, to all intents and purposes, in healthy subjects who were exposed to microwaves in the course of their work. These changes may either become aggravated or abated in the course of further exposure. The dynamics of these functional changes evidently reflects different phases of the response of the nervous and other systems to the detrimental agent. These early reactions include changes in the sensitivity thresholds of certain biochemical processes (Lobanova and Gordon, 1960), activity of the thyroid tissue (Smirnova and Sadchikova, 1960), and the contents of protein, protein fractions and histamine in the blood serum (Gel'fon and Sadchikova, 1960, 1964). The protein composition of the blood may even return to normal during a certain period, despite the continued exposure to microwaves. However, the clinical manifestations become more distinct with increasing length of employment, even though the subject is exposed to low microwave irradiation intensities, i.e., the effects are cumulative, as has been confirmed by experiments on animals.

The data were tested in detail for clinico-hygiene correlation in order to elucidate the part played by the intensity and duration of exposure to microwaves and their frequency range in the clinical development of disease.

We succeeded in establishing a certain degree of correlation between the nature and strength of functional changes in the subject and the frequency range and exposure parameters (intensity and duration of microwave irradiation).

As already mentioned, we differentiate exposure to microwaves into periodic exposure to high irradiation intensities, periodic exposure to low irradiation intensities and continuous exposure to low irradiation intensities.

Analysis of the changes with respect to their dependence upon irradiation intensity and duration revealed that the most pronounced results of periodic irradiation with considerable intensities included vascular autonomic disturbances developing into a vasopathic syndrome, with crises of the diencephalic insufficiency type.

An effect of periodic irradiation of high intensities (up to 10 mW/cm^2) was observed by us only for the centimeter range, mainly while testing certain complete radar units. The clinical manifestations produced by these waves were undoubtedly dependent upon the irradiation intensity, but subjects affected suffered vagotonic alterations in the cardiovascular system, with marked bradycardia, persistent hypotension, disturbance of intraventricular conduction, and considerable slowing of the heart rhythm in oculocardiac reflex tests.

In the case of other wave ranges (millimeter and decimeter waves), and due to the specific working conditions, one encounters, as a rule, periodic or continuous exposure of much lower irradiation intensities (tenths and hundredths of mW/cm^2).

Continuous exposure to low-intensity microwaves generally resulted in disturbances of the nervous system, in particular an asthenic state, obviously due to exhaustion of the CNS. The vagotonic changes were less pronounced in this case.

In addition to the general similarities of effects produced by microwaves, there are some specific differences between different frequency ranges, in particular with respect to the incidence and strength of the changes observed.

For instance, changes in the cardiovascular system are more frequent and pronounced in personnel working with sources of millimeter waves and exposed mostly to low-intensity periodic irradiation. These changes manifest themselves as marked vascular hypotension, often combined with bradycardia and myocardial dystrophy. Trophic disturbances have also been reported (Orlova, 1959).

Changes in the CNS were predominant in personnel working with low-intensity sources of decimeter and centimeter waves.

Comparison of clinical observations on subjects exposed periodically to low-intensity centimeter or decimeter waves did not reveal any significant differences between the two wave ranges.

Reactions to different wave ranges at identical intensity are of considerable interest. Their specific features are probably due to the biophysical properties of the microwaves (penetration and absorption depth).

The strongest vagotonic reactions (hypotension, bradycardia, changed cardiac conduction), often preceding development of asthenic state, occurred in periodic or regular exposure to low-intensity millimeter waves (tenths or hundredths of mW/cm^2). Periodic or regular exposure to centimeter or decimeter waves of the same intensity produced less pronounced and less frequent vagotonic reactions but more pronounced asthenic manifestations.

Millimeter waves are completely absorbed by the skin and evidently affect its receptors directly. Centimeter and especially decimeter waves are only slightly absorbed by the skin, most of their energy penetrating much more deeply. Therefore, we assumed that the pronounced vagotonic reactions observed upon exposure to millimeter waves were mainly of a reflex nature, whereas the asthenic manifestations, especially pronounced with exposure to low-intensity centimeter and decimeter waves, could also be the result of a direct effect on the cerebral structures.

The above assumptions were confirmed by experimental data.

Chapter IV

EXPERIMENTAL STUDIES OF THE BIOLOGICAL EFFECT OF THE SHF FIELD

In our experimental studies, we have concentrated mostly on the long-term effect of low-intensity microwaves, in order to approximate, as closely as possible, actual industrial conditions.

The aim of our work was to elucidate the initial functional and morphological changes in the organism. This included the development, nature and strength of the changes. their dependence on the microwave range, intensity and exposure time, the investigation of possible cumulative effects and sensitivity of specific organs and functions to irradiation. We hoped that classification of the fundamental mechanisms of action, in conjunction with our clinical and hygiene data, would allow us to quote permissible levels of irradiation for humans and control the detrimental effects of microwaves.

In accord with previous experience. experimental studies were primarily concerned with the effect of microwaves on the CNS and certain cardiovascular functions.

The animals' general condition, weight dynamics and survival were used as general indexes of the effect of microwaves. Specific studies were made on the functional state of the autonomic nervous system, including temperature and vascular (blood pressure) control, and on the CNS (the higher nervous activity, the electrical cerebral activity, the sensitivity to audio stimulus, etc.). Morphological studies, characterizing reversible or pathological alterations due to irradiation, were also carried out.

The investigations were performed for a variety of range, intensity, duration and multiplicity of exposure to the microwaves. Experimental conditions were so arranged that animals grouped according to weight, age and sex were screened repeatedly before irradiation, during irradiation, and in a recovery period. The investigations were mainly long-term experiments on rabbits, rats and mice. Results underwent statistical processing.

In the following section the author's results will be presented after those of other investigators.

Methods for experimental irradiation of animals

The following two methods have been used for microwave irradiation of experimental animals.

The first, remote irradiation, method permits determination of the intensity of SHF energy incident on the animal's body surface, by measurement or calculation of the power flux density at the site occupied by the animal.

The irradiation intensity is controlled either by adjusting the distance from the radiator or by varying the output power of the generator (by means of a special power regulator).

The animal chambers were so placed that the axis of the horn antenna passed through the center of symmetry of the front wall of the chamber, which was perpendicular to the axis of the horn radiator.

The second, contact, method permits determination of the microwave energy absorbed in the irradiated body area. It was proposed by Boyle et al. (1950) and by Presman (1958) and calls for direct contact of the irradiated area with the radiating horn. The dosing attenuator and power indicator permit adjustment of irradiation to the desired level of intensity.

According to calculations, this irradiation method produces uniform distribution of power flux density, with only slight attenuation (~ 10%) toward the cage edges. The method is, however, applicable only to irradiation of a single small animal.

Methods for the positioning of animals for irradiation offer considerable variety. For instance, Ely and Goldman (1956) suspended animals (rats and rabbits) in nets and dogs by canvas suspenders. Kuttig (1955) irradiated rats in paper cages. Other investigators placed their animals in wooden boxes, chambers, etc.

We resorted mostly to group irradiation of animals.

Rats and mice were irradiated in special polystyrene cages of dielectric constant $\epsilon = 2.4 - 2.9$ and dielectric loss-angle tangent $0.0002 - 0.0003$, so that reflection of waves from the irradiated front wall of the cage is small, while energy losses within the walls are negligible.

The cage for rats consisted of 6 to 9 compartments in 2 or 3 tiers, with one animal in each compartment (Figure 3). Each compartment has an area 18×5 cm and height 8 cm.

A special 3-tier chamber was designed for irradiation of rabbits (Figure 4).

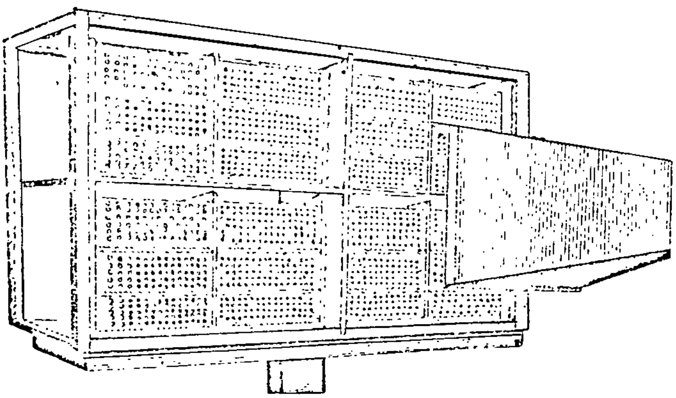

FIGURE 3. Cage for irradiation of rats

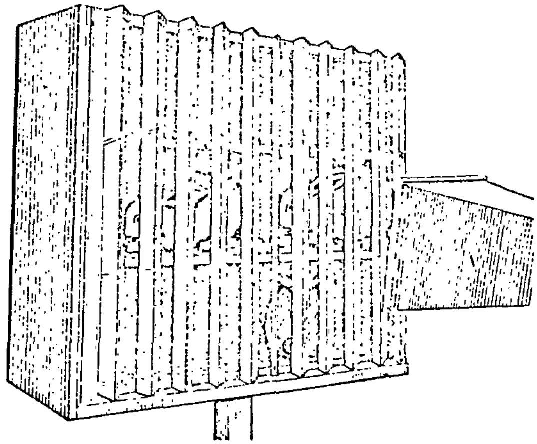

FIGURE 4. Chamber for irradiation of rabbits

The chamber was made of 8-mm plywood. Trihedral prismatic bars of polystyrene constituted the front part of the chamber, facing the radiation source. The bars kept the animals within the chamber, but at the same time were practically transparent to the incident energy flux. The movable chamber wall was covered with sheets of energy-absorbing material.

Testing of methods for the positioning of animals showed that the chamber and cage permitted normal irradiation conditions and dosing of the microwave energy.

The animals were irradiated by radar transmitters working in different frequency ranges, with both pulsed and sustained irradiation patterns (Luch-58). Rectangular or conical horn antennas were used as the radiating device in all cases. Both continuous and pulse radiation were dosed at this mean power level.

*

Survival of animals under microwave irradiation

Survival of animals exposed to UHF electric fields has been investigated by many authors, but nearly all the reports have failed to give data on irradiation intensities. At best, mention has been made of the generator output power. All the investigators have described lethal results for the experimental animals, subsequent to marked hyperthermia, heightened respiration, tachycardia and rapid rigor mortis (Suponitskaya, 1933; Slavskii et al., 1933; Lebedinskii, 1940; Anikin and Varshaver, 1950). According to certain investigators, the experimental animals died at a lower temperature than animals killed by ordinary heating.

The effect of microwaves on the survival of animals has been reported in several papers.

Tutkevich (1940) observed rapid death of animals (rats) irradiated with decimeter waves the rise of their body temperature being only 1.5 — 2°C.

According to Hines and Randall (1952), very high intensities of irradiation with 10-cm continuous waves produced a very high lethal effect, depending upon the irradiation time; death was caused by thermal paralysis of the respiration center. The irradiation intensities were obviously very high, since the lethal outcome was produced by exposures of only a few seconds.

Cogan et al. (1958) irradiated rabbits with decimeter waves (468 mc) of intensity 30 and 60 mW/cm^2 and observed a lethal outcome with exposures of 120 and 30 min, respectively.

Prausnitz and Susskind (1961) reported death of animals after 12 min upon irradiation with microwaves of intensity 0.1 W/cm^2 and after 3.75 min upon exposure to an intensity of 0.270 W/cm^2. The survival of mice was not affected by preliminary long-term irradiation with lower intensities.

A different opinion was advanced by Michaelson et al. (1961), who demonstrated adaptation of their experimental animals (dogs) to repeated microwave irradiations, manifesting itself in satisfactory and prolonged tolerance to repeated subsequent irradiations.

Deichmann et al. (1959) demonstrated that for identical irradiation intensity, animals were killed by microwave irradiation eight times faster than by infrared irradiation. and the rise of their rectal temperature was four times higher in the former case.

The degree and nature of injuries to animals are dependent on the dimensions and localization of the irradiated area. For instance, Deichmann et al. (1959a) showed that irradiation of rats with electromagnetic waves of frequency 24.000 mc (1.25 cm) and of considerable intensity (300 mW/cm^2) killed the animals after different exposures, depending upon the localization of the irradiated area, i. e. in 12.3 min for the abdominal area, in 18.5 min in the case of the head and in 15.5 min for the lumbar region. Furthermore, the nature of the animal's reaction to irradiation was similarly linked with the localization of the irradiated area. Irradiation of the head produced central nervous excitation, while irradiation of the lumbar or abdominal region or total irradiation of a rat produced marked overheating.

In addition to irradiation intensity, the duration of exposure and the size and localization of the irradiated area affect the survival of animals in an SHF field.

Deichmann et al. (1959b, 1961) showed that animals irradiated with centimeter waves (24,000 mc) of high intensity (up to 250 mW/cm^2) survive longer at lower ambient temperatures. For instance, irradiated animals died in 17.4 min at an air temperature of 35°C but in 47 min at 15°C. According to the same authors, rats lived much longer, up to 14—24 hr, if they were ventilated with a stream of air at 15°. Clearly the rats' survival time is largely dependent upon the animal's ability to give up heat generated by absorption of SHF energy in their tissues. Indeed. reduction of the ambient temperature from 50° to 23° increased the animals' survival period fourfold, and at the same time the animals' rectal temperature dropped by 4°C. Similar results were obtained by Carpenter et al. (1961).

Investigations carried out in our laboratory (Lobanova) were designed to clarify the clinical picture of animal survival in relation to the frequency range of the SHF field and to the intensity and duration of irradiation.

Investigation of animals' survival preceded other investigations (such as lethal irradiation), since it was necessary to establish the accuracy of dosimetry, the feeding and maintenance conditions for the animals, sublethal intensities and durations for long-term exposures.

The investigations were carried out on 470 male albino rats weighing 195—205 g. The animals which survived the irradiation were kept under observation for three weeks.

The clinical picture exhibited by our experimental animals exposed to high-intensity SHF was the same for the entire microwave range and constituted several successive periods.

Period I: orientation reaction; the animals washed themselves.

Period II: the animals became restless, and exhibited mild reddening of the paws, tail, tip of the nose and ears.

Period III: the animals became very restless, scratched at the cage walls and hurled themselves upon them; hyperemia became more pronounced. At this stage, excitation was so strong that narcotized rats regained consciousness.

Period IV: the animals lay prostrate; there was marked hyperemia of the paws, tail, tip of the nose and ears. Occasionally there were clonic spasms and paresis, edema of the head and genitals.

Period V: the animals assumed a lateral position; sanious secretions from the nose and mouth; death.

Periods III and IV also included alternating excitation and depression. No burns were observed.

The following table illustrates a case of irradiation with decimeter waves of intensity 100 mW/cm^2.

In the	6th	minute	— washing;
"	10th	"	— restless behavior;
"	17th	"	— " " — hyperemia of the paws, tail, tip of the nose;
"	23rd	"	— restlessness, scratching at the cage;
"	27th	"	— acute restlessness;
"	33rd	"	— lying quietly, hyperemia;
"	52nd	"	— spasms;
"	60th	"	— death.

The time of appearance and development of the stages and of the animals' death depended on the irradiation intensity and the SHF range.

Table 2 lists data on the survival of animals (rats) irradiated with intensities of 100, 40 and 10 mW/cm^2 in different SHF ranges, generated in the pulse regime.

TABLE 2. Survival time of irradiated animals

Wave range	Time of animals' (rats) death		
	100 mW/cm^2	40 mW/cm^2	10 mW/cm^2
Decimeter	60 (50%)	Survived for 2 hr	Survived for 5 hr
10-cm	60 (100%)	40 (50%)	Same
3-cm	110 (50%)	Survived for 3 hr	"
Millimeter	180 (50%)	Same	"

The tabulated data show that maximum (100%) lethality for a minimum irradiation time (60 min) occurred for the case only of 10-cm waves. No other range produced 100% lethality; furthermore, the time required for 50% lethality was considerably longer, 60 — 180 min. An irradiation intensity of up to 10 mW/cm^2 was readily tolerated by the animals for all the frequency ranges, there being not a single lethal case even with prolonged exposure (> 5 hr).

It must be emphasized that none of the animals surviving irradiation with 100 or 40 mW/cm^2 of different durations died within the following 3 weeks. With an increasing number of sublethal irradiation sessions the animals became more tolerant towards irradiation and were in a satisfactory state after 5 — 10 sessions. The same was observed by Abrikosov (1958) in his experiments with UHF electric fields. Presumably, the animals tolerated the strong irradiation due to functioning of compensatory mechanisms, although the morphological changes remained, or were only slightly modified (Gordon, Lobanova and Tolgskaya, 1955). Subsequently, these tolerated irradiation intensities were used in experiments designed to study the effect of irradiation on the animals' development.

TABLE 3. Survival of animals exposed to different wave ranges

Wave range	Nonlethal exposures for different irradiation intensities		
	100 mW/cm^2	40 mW/cm^2	10 mW/cm^2
Decimeter	30 min	> 120 min	> 5 hr
10-cm	5 "	30 "	> 5 "
3-cm	80 "	> 180 "	> 5 "
Millimeter	120 "	> 180 "	> 5 "

Table 3 gives the intensities and durations of irradiation with microwaves of different ranges tolerated by experimental animals.

The nonlethal irradiation time for intensities, 100 — 40 mW/cm^2, was much shorter in the case of 10-cm waves (5 — 30 min) in comparison to the other frequency ranges (30 — 180 min and longer). Therefore, 10-cm waves are the most dangerous, biologically, for considerable irradiation intensities.

In investigations with different generation patterns of SHF energy (pulse and continuous) Lobanova observed more rapid death of animals and a higher lethality in the case of pulsed 10-cm waves, for the same irradiation intensity, although the same clinical picture of overheating appeared with both regimes.

Different results were reported by Abrikosov (1958) from his experiments with pulse and continuous UHF electric field, for identical irradiation intensities. The mean survival time of mice was much longer (43 min) in the pulsed UHF electric field than in a continuous UHF field (3 min). According to this author, death with exposure to a continuous UHF field is caused by hyperthermia (rise of respiration rate, cyanosis of bare body areas, pronounced motor excitation, rapid rigor mortis). The phenomena are not observed upon exposure to a UHF electric field.

The role of the irradiation pattern and the causes of the different results obtained with frequencies corresponding to 10-cm and ultrashort waves call for further studies.

Attempts, both in the USSR and outside, to establish the exact lethal dose of irradiation have as yet been unsuccessful. Nevertheless, within certain limits of irradiation intensities, comparable results have been obtained.

Thus Deichmann et al. (1959a), who investigated the survival of rats irradiated with 10-cm waves, found that the animals died 15 min after termination of exposure to irradiation of intensity and exposure time in the ranges 45 to 260 mW/cm^2 and 91 down to 24 min, respectively.

Table 4 gives rough calculations of data chosen randomly from Deichmann. It shows that comparable doses produced similar effects and these results can be corroborated by our investigations on rats (Table 5).

TABLE 4. Lethal dosage (random selection based on Deichmann's data)

Irradiation intensity, mW/cm^2	Minimum lethal exposure, min	Dose, $mW/cm^2 \cdot hr$
150	35	87
97	45	73
78	56	73
57	80	76
45	91	68

TABLE 5. Lethal dosage (data of our laboratory)

Irradiation intensity, mW/cm^2	Mean lethal exposure, min	Survival time after exposure	Dose, $mW/cm^2 \cdot hr$
100	60	Immediate death	100
40	120	Same	80

Irradiation doses for the range of intensities (100 — 40 mW/cm^2) were comparable to those observed by Deichmann.

Table 6 shows results over an extended range of doses (taken from Deichmann).

TABLE 6. Lethal dosage (random selection based on Deichmann s data)

Irradiation intensity, mW/cm^2	Minimum lethal exposure, min	Survival time after exposure	Dose, $mW/cm^2 \cdot hr$
260	43	Immediate death	186
35	135	Same	79
28	139	"	65
24	450	Remained alive	180

Different doses were required to produce the same effect for high or low irradiation intensities. Thus, a slight decrease of intensity (by 4 mW/cm^2) allowed survival of the animals throughout a considerably increased irradiation time. There are evidently intensity thresholds at which the time factor becomes of minor importance and it is therefore impossible to calculate an exact lethal dose.

The tolerance of animals to microwave irradiation is strikingly affected both by the external temperature (Deichmann's experiment) and by changes in diet and physical stress.

In investigations on the salt and water requirements of animals irradiated with centimeter waves we maintained the animals on a special periodic diet (Kulakova, 1964). They were kept twice weekly for 24 hrs on a solution of 20% glucose with small additions of various salts. The 24 control rats thrived on this diet and their weight did not change. Twenty-four experimental rats. irradiated daily with 10-cm waves (40 mW/cm^2) for 15 min and kept on an ordinary diet, were in a normal state. Of the 24 rats irradiated daily with 10-cm waves for 15 min and maintained on a glucose regime twice weekly for 24 hr (2—4 weeks) 12 died, mostly after 5—11 irradiation sessions. The animals which survived the first irradiation cycle (23 sessions) were kept on the same diet and irradiated again after one month. Of these animals 5 perished after 4 further sessions, in contrast to rats maintained on an ordinary diet; these survived.

The tolerance of animals to irradiation is much impaired by water deprivation. A small water deficiency may cause animals, that have been subjected to long-term low-intensity irradiation for months, to perish at the next irradiation. Thus, 13 rats out of a total of 45 died after deprivation of water twice during two weeks. Control animals, deprived of water but not irradiated or not deprived of water but irradiated, survived the treatments.

Exposure of animals to sublethal doses modified their tolerance to physical stress.

Experiments by Lobanova on 76 rats subjected to the stress of swimming after a single irradiation with doses of 100 mW/cm^2 down to 10 mW/cm^2 demonstrated that the swimming time of these animals (even those irradiated with 10 mW/cm^2) was considerably shorter than that of the controls.

Hence, exposure to microwaves of even low intensities greatly impairs the animals' tolerance to physical stress, and changes in the diet or water intake accelerate their death. The exposure time is also important in this respect.

The above data permit certain conclusions to be drawn.

1. There is an inverse relationship between the irradiation intensity and the time elapsing until death of the irradiated animals.

2. The reaction of animals to exposure to microwaves (decimeter, centimeter and millimeter) always involves the following three periods: an orientation period; an excitation period; and a passive period (with occasionally spasms) leading to death.

3. Death is caused by overheating, as indicated by motor excitation, hyperemia, pareses and rapid rigor mortis. The overheating is due to absorption of the incident SHF energy and its conversion to thermal energy by dielectric losses in the tissues. There is evidently also a direct effect of microwaves on the thermoregulatory centers.

4. The most rapid lethal outcome is produced by irradiation with 10-cm waves of considerable intensities; the effect of decimeter, 3-cm and 5-mm waves is less pronounced.

5. For the same intensity of radiation with pulsed and continuous 10-cm waves, lethality is higher and more rapid with pulsed waves.

6. The survival of animals irradiated with microwaves, of even low intensities, may be affected by changes in their diet or water intake. Irradiation impairs the animals' tolerance to subsequent physical stress.

Weight dynamics of animals under long-term exposure to microwaves

Studies on the development and especially on the weight variation of irradiated animals have been reported in several papers.

Nikonova (1961) demonstrated that prolonged (4-month) exposure of young rats to high-frequency electromagnetic waves (500 kc), with an electric field component of 200 — 500 V/m and magnetic component of 60 and 150 amp/m, did not produce weight changes compared to the unirradiated control rats. Golysheva and Andriyasheva (1937) found a deviation in the weight of irradiated young mice compared to the controls, as the frequency was increased from 33 to 120 Mc (UHF). The animals' growth was stimulated by small doses and inhibited by large ones. Tikhonova (1948) confirmed the effect of small UHF doses on animals' development. Harmsen (1954) could not detect significant differences in the weight of experimental and control rats after irradiation of the former for 22 weeks in a UHF field of 77 V/m.

Work on the effect of SHF (300 — 300,000 mc) on animal development has been limited in scale. Denier (1933) demonstrated a stimulatory effect of small doses of decimeter waves on guinea pigs' weight dynamics.

Kuttig (1955) investigated the development of albino rats irradiated with centimeter waves ($\lambda = 12.4$ cm). The irradiation intensity could be calculated approximately as 40 — 50 mW/cm^2, since unfortunately the output generator power, only, was reported in this paper. No difference in the development of irradiated and control animals was observed.

Our laboratory has produced two papers concerned with the effect of irradiation of high and low intensity 10-cm waves on the growth of rats (Lobanova, 1960).

These papers showed that in the first weeks of irradiation a somewhat larger weight increment occurred in rats treated with the 10-cm waves than in the controls. For both low and high intensities approximately the same total dose was applied. Thus, with intensities of 10, 40, 110 mW/cm^2 the exposure times were 60, 15 and 5 min, respectively.

Experimental data on the stimulation of growth by brief and repeated high intensity irradiations do not warrant conclusions as to a beneficial effect of the treatment. Indeed, such irradiations produce certain histological symptoms including moderate degenerative changes in parenchymatous organs and the nervous system, although the animals remain more or less healthy and continue to gain weight.

Protracted irradiation (2 – 6 months) caused the weight of experimental animals to lag behind that of controls and produced more profound and irreversible morphological changes.

Recent long-term experiments with other SHF ranges have revealed certain characteristic responses.

The investigations were performed on 493 adult male animals including 213 albino rats weighing 150 – 160 g and 280 white mice weighing 18 – 22 g, which were divided into groups and treated with millimeter 3- and 10-cm and decimeter waves of intensity 10 mW/cm^2. Each irradiation session was of 60 minutes. The animals were irradiated daily for 6 – 8 months.

Data on the weight increments of the irradiated and the control animals are listed in Table 7.

TABLE 7. Weight variations of animals exposed to microwaves

Wave range	Irradiation intensity, mW/cm^2	Onset of changes, months	Weight increment of animals, g (mean data)	
			irradiated animals	controls
Decimeter (rats)	10	2	95	120
10-cm (rats)	10	1.5	25	70
10-cm (mice)	10	1	0.5	2.9
3-cm (rats)	10	1	42	70
Millimeter (rats)	10	3	65	75

As can be seen, low intensities (up to 10 mW/cm^2) over the entire microwave range cause a lag in the weight of the experimental animals compared to the controls, after 1 – 2 months of irradiation.

Response of animals to the heating effect of microwaves

The thermal response of living organisms to radio frequency electromagnetic waves over considerable intensities is beyond doubt and has been recognized by all investigators. The degree of the heating effects depends on the irradiation intensity and duration, the frequency range and the level of energy absorbed. Once absorbed in the living tissues, the radio frequency energy is converted to heat which is conducted away. Only a few papers have dealt with the temperature response of living organisms to irradiation with long and medium waves.

Khazan, Goncharova and Petrovskii (1958), Kalyada, Kulikovskaya and Osipov (1959) and Smurova et al. (1962) have reported a slight rise, or a tendency to such a rise, of body temperature in personnel working with sources radiating medium waves (HF field). In our opinion, slight fluctuations of body temperature in field conditions may result from several causes independent of the HF field (e.g., high air temperature at work sites during high-frequency hardening of metals, infrared radiation from hot components, etc.). Furthermore, Presman's biophysical calculations (1960) do not support the assumption that the strengths of HF fields actually used in industry can raise the temperature of the human body.

In this connection, special interest attaches to the investigations carried out by Nikonova (1961) in our laboratory. The HF field was produced by a specially designed generator enabling exposure of the experimental animals (rabbits and albino rats) to electric and magnetic fields of different strength (electric fields of 350 to 8,000 V/m and higher, magnetic fields up to 160 amp/m). The investigations revealed a statistically significant rise in the rectal temperature of 0.3°C, at an electric field strength of 8,000 V/m. This field strength is probably the lower limit of that which produces a thermal response. No rise in body temperature was produced by a magnetic field of 160 amp/m.

Most investigators have reported rises in the body temperature of personnel working with shorter wave sources (SW and USW). Khazan et al. (1958) reported a temperature rise of 0.1°C in a group of people working with SW generators (20 Mc — 15 m). Plotnikov and Martens (1940) failed to observe a rise in the body temperature of rabbits exposed to 16 — 18-m waves for one hour, while Golysheva (1937) detected a rise of 0.2 — 0.3°C in guinea pigs exposed to high intensities.

Generation of heat by USW (1 — 10 m) is a well-known phenomenon, used extensively in therapy. In the overwhelming majority of investigations no assessment of irradiation intensity has been provided, making it impossible to determine the threshold of the heating effect. However, several authors have confirmed the temperature rise in animals exposed to ultrashort waves (Slavskii, Shmidt and Burnaz, 1933; Didenko, 1940; Golysheva, 1937; Suponitskaya, 1933, 1937; Abrikosov, 1958; and others).

A rise of body temperature was also detected in personnel servicing UHF generators, under industrial conditions (Khazan et al., 1958; Kalyada et al., 1959; Shapiro, 1940; and others). According to certain authors, the body temperature rose to as high as 39°C (Kalendarov, 1934). A rise of human body temperature under the influence of short waves was observed by Slavskii, Shmidt and Burnaz (1933), Piontkovskii (1934), Omelyants (1935), Lebedinskii (1937) and others.

No effect was detected in human subjects irradiated with ultrashort waves (50 mc) of very low intensity 25 V/m (Baronenko and Timofeeva, 1958). Several investigators have noted a certain lowering of the body temperature upon local irradiation of animals (Popov, Gubarev, Vadimova and Malevannaya, 1940; Turkevich, 1940). Similarly, Abrikosov (1958) reported a drop of the rectal temperature in animals irradiated with pulsed UHF electric fields. He attributed the phenomenon to a specific effect on the higher divisions of the nervous system.

The role of the nervous system in thermoregulation upon exposure to low intensity UHF waves was investigated by Slavskii et al. (1933). According to Tonkikh (1940), neurotomy of the cervical sympathetic nerves in cats or rabbits diminished the temperature rise induced by the irradiation.

Golysheva and Gal'perin (1941) suggested that impulses arriving via the sympathetic system affect the higher autonomic centers and cerebral cortex, with attendant modification of heat production. Intensified heat production was also proposed as an explanation for the rise in the body temperature of irradiated animals (Suponitskaya, 1933; Golysheva, 1941).

In investigations of the response of animals to short (14.88 Mc) and ultrashort (69.3 Mc) waves Fukalova (1964) established the maximum intensities which did not raise the body temperature. These maximum intensities were 2,250 V/m in the SW range and 150 V/m in the USW range. A pronounced heating effect was caused by short and ultrashort waves, whereas medium waves produced a very weak effect even at high intensities (8,000 V/m).

The temperature response of organisms to continuously generated microwaves in the 10—12-cm range was studied by several workers, to whom in addition the temperature gradients were of special interest. Certain investigators (especially outside the USSR) have aimed at correlating the organism's response to irradiation with the rise in body or organ temperature. Thus, for example, attempts have been made to establish the dose of 10-cm waves producing cataracts from the temperature of the ocular tissues. It is suggested that in conditions in which no appreciable heating of surface tissues occurs, there is a minimal danger of overheating deep-seated ocular tissues. Such studies also provide information on optimal conditions for general or local heat therapy.

These researches have given rise to three points of view in regard to the state of temperature gradients.

Certain groups of authors concluded that microwave irradiation produces a higher temperature rise in deep-lying tissue than in the surface layers, i.e., a positive temperature gradient is assumed to coincide in direction with that occurring naturally. The gradient is manifest to a comparatively small depth of 2—3 cm. This school of thought has been represented by Krusen et al. (1947), Leden et al. (1947), Wakim et al. (1948), Gersten et al. (1949), Engel et al. (1950), Ladeburg and Schareck (1951) and Tyagin (1957).

Another group of investigators, represented by Osborn and Frederick (1948 and 1949), Rae et al. (1949) and Murphy et al. (1950), held that the absolute gradient diminished with increasing depth and that the temperature of the surface layers after irradiation considerably exceeded that of the deep-seated layers.

Conflicting results, held in support of either point of view, were probably due to differences in experimental aims and procedures, in irradiation intensities, temperature recording techniques and in the depth of measurement of tissue temperatures, etc.

Most workers have recognized the possibility of both positive and negative gradients depending upon the irradiation intensity and duration and on the size and localization of the irradiated body area (Worden et al., 1948; Horvath et al., 1948; Seguin and Castelain, 1947; Boyle, Cook and Buchanan, 1950; Cook, 1952; Kemp et al., 1948; and others). The more accurate and comparable results have been obtained by the contact method of local irradiation and by measuring the tissue temperature soon after irradiation (30—60 sec).

Mention should be made of Tomberg's (1961) theory that the largest temperature gradient occurs in boundary layers of tissues. This may be due to nonuniform absorption of energy in the boundary structures of the organism, the heterogenous dielectric and thermal conductivity properties of which allow the setting up of nonuniform electric fields as temperature gradients, respectively.

After 1950, several reports appeared of calculations (Schwan and Li, 1955) or determinations of the threshold for local and whole-body irradiation of animals with centimeter waves (Ely and Goldman, 1956; Gordon, 1957; Tyagin, 1957; Gordon and Lobanova, 1960).

The intensity threshold for a full heating effect was established as 10 mW/cm^2. According to Presman (1957), 5 mW/cm^2 is required to raise the skin temperature after local irradition of the human interior scapular surface with 11-cm waves.

Tyagin's interesting research (1957) into whole-body irradiation of different species demonstrated that the response was dependent not only upon the irradiation intensity but also upon the animal's size and the quality of its thermo-regulatory apparatus. For instance, very intensive irradiation (300 mW/cm^2) raised the rectal temperature by 1—1.5°C in dogs, 6.6—7°C in cats and rabbits and 7.9—10°C in rats.

Boysen (1953), who investigated the effect of the mode of generation of decimeter waves, concluded that pulsed irradiation caused larger energy absorption than continuous irradiation. This view was shared by Tomberg (1961), who reported that exposure of a heterogenous object to an SHF field generated a larger thermal effect during pulse modulation.

The time required for the maximum local or whole-body heating of animals has been determined by many investigators. Worden et al. (1948) observed maximum local heating of tissue following 20 min of irradiation with 0.4 W/cm^2 centimeter waves; Gersten et al. (1949) and Murphy et al. (1950) observed heating after 15 and within the first 10 minutes, respectively.

Upon irradiation of rats' lumbar region ($\lambda = 1.25$ cm; intensity 0.3 W/cm^2) Deichman et al. (1959) were able to measure a considerable rise of temperature ($\Delta t = 8.5°C$) in the irradiated area after only 1.5 min and a similar substantial rise of the rectal temperature ($\Delta t = 6.1°C$) after 20 min.

Tyagin (1957, 1960) related the rise time of temperature during whole-body irradiation to the species and the irradiation intensity. The smaller the animal and the higher the intensity, the more rapid was the rise of the temperature. It occurred immediately in rats and after 1—3 min in rabbits exposed to 0.3 W/cm^2, and after 2—3 or 4—5 min, respectively, in rats and rabbits exposed to 0.05 W/cm^2. In our opinion, these data scarcely permit a discussion of the rise time and dynamics of the temperature response, since intensities of 0.3—0.4 W/cm^2 lead to acute overheating and rapid death of the animals.

All the above investigations of the overheating response were concerned only with the centimeter range of the microwaves.

A few reports have dealt with the reaction of animals to high intensity decimeter waves. Howland et al. (1961) and Michaelson et al. (1961, 1961a) demonstrated that for identical intensities of 100—165 mW/cm^2, centimeter waves ($\lambda = 10.7$ cm) produced a stronger thermal effect than decimeter waves ($\lambda = 150$ cm).

Our investigations (Gordon and Lobanova, 1960; Lobanova, 1964) have been designed to indicate microwave intensities suboptimal for the generation of the heating effects. This work naturally preceded studies of principal interest to us, i.e., the biological effect of low irradiation intensities.

The rectal temperature was taken as an index of the overall heating effect. Its value reflects thermoregulation in the entire body, and it is thus clear that the absence of a temperature rise in the rectum does not exclude the possibility of such an effect in tissues and internal organs absorbing microwave energy selectively. Temperature was measured with a copper-constantan, thermocouple or a mercury thermometer, within ± 0.1°C.

Two hundred albino rats each weighing 150—200 g were the experimental subjects of our research.

Table 8 presents measurements of the body temperature of rats subjected to microwave irradiation of various frequencies, ranges and intensities, for a constant exposure time of 15—30 min.

TABLE 8. Rectal temperature of animals irradiated with microwaves

Wave range	Irradiation intensity, mW/cm^2	Δt (°C) (in comparison to controls)	m of the difference
Decimeter	40	0.1	0.17
10-cm	40	1.0	0.07
Same	10	0.2	0.12
Millimeter	40	0.7	0.07
"	10	0.3	0.08
"	5—7	0.1	0.1

Decimeter, centimeter and millimeter waves produced rises in rectal temperature at different threshold intensities. The limiting suboptimal intensities were, respectively, 5—7 mW/cm^2 for mm waves, 10 mW/cm^2 for 10-cm waves and >40 mW/cm^2 for dm waves. Hence, millimeter waves are the most thermogenic for low irradiation intensities. It may be assumed that millimeter waves, being absorbed mainly in the superficial skin layers, affect the numerous receptors and produce a reflex reaction in the body. Marked changes in the skin receptors under such conditions have indeed been revealed in morphological and histochemical tests.

In Table 9 we present limiting energies of a range of radiowaves, producing thermal effects. Units are expressed in the form of energy densities ($ergs/cm^3$).

TABLE 9. Irradiation energies suboptimal for the raising of body temperature

Radiofrequency range	Heating effect threshold	Energy density, $ergs/cm^3$
Medium	Below 8,000 V/m	$2,830 \cdot 10^{-6}$
Short	" 2,250 "	$224 \cdot 10^{-6}$
Ultrashort	" 150 "	$0.995 \cdot 10^{-6}$
Decimeter	Above 40 mW/cm	$13.2 \cdot 10^{-6}$
Centimeter	" 10 "	$3.3 \cdot 10^{-6}$
Millimeter	" 7 "	$2.31 \cdot 10^{-6}$

It can be seen that the energy densities decrease monotonously with increasing frequencies (diminishing wavelengths), except in the USW range.

The incident energy of a field (PFD or energy density) is, however, far from being the only factor controlling the energy absorbed by a given biological object. Wavelength, the object's shape, dimensions, electrical properties and orientation to the field, the presence of reflecting surfaces, and the animal's mobility, all affect the absorption of energy. Anne et al. (1961), Franke (1960), and others have calculated that the energy absorbed by an object in the field of a plane wave (for a constant orientation of the object and constant field strength) first increases monotonously with frequency, then falls sharply (when the size of object becomes one-half the wavelength), and then remains practically constant.

Our experimental conditions were not strictly identical with those for which calculations were made, involving amongst other factors: absence of a plane uniform field, presence of reflecting surfaces, some experiments being carried out in a resonator or condenser, no direct determinations of effective absorbing surface. The results were, however, in qualitative agreement with the calculations and it was thus assumed that the increment of the animal's body temperature was related to the amount of absorbed energy.

The results for the USW range cannot as yet be explained, but the specific features of this range may be due either to the similarity of the rat's dimensions to the wavelength, or to possible resonance effects in the macromolecules of heterogenous structures (Bach, Luzzio and Brownell, 1961; Cook, 1952; Moskalenko, 1960; Franke, 1960).

We have compared the response of animals to pulsed or continuous 10-cm microwaves. By utilizing low intensities we established the criterion of response as the presence or absence of a thermal effect, rather than the rate of rise of temperature. Intensities of 2.5, 5, 7.5 and 10 mW/cm^2 were tested.

Table 10 shows the body temperature increments in 58 rats irradiated with continuous or pulsed microwaves for 30 min.

TABLE 10. Increment of body temperature upon exposure to continuous or pulsed 10-cm waves

Irradiation intensity, mW/cm^2	Continuous radiation, λ = 10 cm	Pulsed radiation, λ = 10 cm
	Δt (°C)	Δt (°C)
2.5	-0.3	-0.2
5.0	-0.2	-0.3
7.5	-0.3	-0.1
10.0	+0.3	+0.1
Control animals	-0.1	-0.1

Statistical analysis of 1,000 measurements showed that neither pulsed nor continuous SHF waves of intensity 2.5—7.5 mW/cm^2, produced a significant change in rectal temperature compared to that of unirradiated animals, except for a small downward trend.

Only after continuous irradiation of 10 mW/cm^2 was the rectal temperature somewhat higher (0.4°C) than in the controls. At this intensity pulsed waves produced no change in body temperature. Our data agree with Abrikosov's for the range of ultrashort waves. It is our opinion, however, that the phenomenon still lacks an explanation.

We have been especially interested in the dynamics of the overheating reaction in animals irradiated with intensities bordering on limiting values. Rats' rectal temperature was measured at 5, 10, 15 and 30 min during irradiation with 10-cm waves of intensity 16—28 mW/cm^2 and in unirradiated control animals. Table 11 gives data on the variation of the irradiated animals' temperature relative to the controls. There is a small rise of rectal temperature after a 5-min exposure (0.4°C), but this falls to a constant temperature increment of 0.1—0.2°C after 10—15 min.

TABLE 11. Dynamics of the heating response of rats irradiated with 10-cm waves

Time of exposure, min	Temperature increment, °C: Δt in recto
5	0.4
10	0.2
15	0.1
30	0.2

Similar results were obtained upon irradiation with other ranges of radiowaves. Of all the range of wavelengths tested the temperature rise was the most rapid with centimeter waves, and this may explain the swifter lethal outcome caused by these microwaves.

The rate of the temperature rise in an animal is affected by its capacity for thermoregulation after exposure. In all our investigations, the animal's temperature was measured immediately after irradiation and also 30 or sometimes 60 min later.

Table 12 describes the dynamics of the temperature response of animals irradiated with pulsed 10-cm waves.

TABLE 12. Recovery of normal temperature after irradiation

Irradiation intensity, mW/cm²	Δt (°C)		
	immediately after irradiation	30 min after irradiation	60 min after irradiation
100	1.9	1.3	0.6
40	1.0	0.1	—
10	0.2	0.1	—

The rectal temperature was normal 30 min after an irradiation intensity of 40 mW/cm^2, while body temperature had not recovered even 60 min after irradiation of 100 mW/cm^2, indicating considerable disturbance in the body's thermoregulation. The latter state may persist for 180 min and longer.

In summary, the above data lead to the following conclusions:

1. The threshold intensity for production of a whole body heating effect (a rise of rectal temperature) differs for different microwave ranges. The lowest thermal threshold occurs in the case of millimeter waves followed by 10-cm and finally decimeter waves.

2. Continuously generated SHF energy of intensity 10 mW/cm^2 produces a small rise of body temperature (0.4°C) but no rise occurs with pulse modulation of the same intensity.

3. Investigation of the dynamics of the overheating response revealed that a stable rise of body temperature occurred after a 10—15-min exposure. The dependence of the temperature increment upon exposure is the most pronounced for the 10-cm microwave range.

4. Animals recover their original body temperature 30—60 min after irradiation of intensity 40 mW/cm^2, but only after 180 min for irradiation of very high PFD (100 mW/cm^2).

Effect of microwaves on blood pressure

The effect of radio-frequency electromagnetic waves on the vascular tonus of human subjects and experimental animals has been investigated by several authors.

The medium wave range was observed, by Osipov (1953), Machabeli et al. (1957) and Smurova et al. (1962), to induce hypotension of vagotonic origin in personnel working with industrial high-frequency generators. Practicing physiotherapists Omelyants (1936) and Popov (1940) confirmed a hypotensive effect of d'arsonvalization on human subjects. Of the few experimental investigations into the effect of HF fields on blood pressure that of Nikonova (1963) deserves mention. Rats were subjected to a 10-month exposure to a high-frequency electric field of 1,800 V/m and a magnetic field of 50 amp/m. The blood pressure of the albino rats was depressed, more so by the magnetic field than by the electric field.

Hypotension in personnel working with UHF sources under industrial conditions has been reported by Shapiro (1940), Osipov (1952) and Kalyada, Kulikovskaya and Osipov (1959). Similar results were obtained by Arinshtein et al. (1936), Lebedinskii (1937) and Baronenko and Timofeeva (1958). Extensive data concerning the effect of UHF electromagnetic waves on blood pressure are available as a result of their use for physiotherapeutic purposes, including the treatment of hypertension (Likhterman, 1936; Orlov, 1938; Mezhebovskii and Sverdlova, 1939; Glebova and Vasina, 1948; Shulkova, 1949; Fisher, 1956; Abrikosov, 1958; Schliephake, 1933, 1949; Libesny et al., 1935; Laubry et al., 1937; and others). Investigations into the hypotensive effect of UHF fields on experimental animals have also been numerous (Slavskii, 1936; Vannotti, 1936; Skipin and Baranov, 1934; Parin and Davydov, 1940; Aronova, 1955; Abrikosov 1958; and others).

Several of the above-mentioned authors attempted to elucidate the mechanism of the hypotensive effect of UHF fields. Experiments with narcotized animals or with denervated limbs led to the conclusion that the hypotension is of reflex origin.

Abrikosov (1958) compared variations in arterial pressure under the influence of both continuous and pulsed UHF electric fields, while utilizing both as physiotherapeutic agents. He found that the trend and rate of variation of arterial pressure in animals subjected to a single irradiation differed for pulsed and continuous UHF fields. Pulsed UHF fields caused a rapid depression of the blood pressure, whereas a continuous field may also produce some rise in the pressure or no change at all. According to this author, the cause of the hypotension is a neural reflex which is quite independent of the heating effect of the UHF field. We are in agreement with this point of view.

More recent work by Obrosov and Yasnogorodskii (1961) has confirmed that the organism reacts to a pulsed UHF electric field (50 mc) of low intensity by a drop in blood pressure, especially after a state of initial hypertension. This result was interpreted as being due to an intensification of inhibition processes in the central nervous system.

Several investigators (Frenkel, 1940; Glezer, 1940; Roffo, 1935) reported a hypertensive effect in experimental animals, but this is explicable by the finding of Kharitonov (1940), who discovered a 2-phase response to a UHF field in a short-term experiment on dogs. The response involved a transient rise of blood pressure, followed by a drop.

Thus, most workers have confirmed a pronounced hypotension or at least a downward trend of blood pressure in humans and animals upon exposure to HF and UHF fields. The occasional failure to observe such effects may be attributed to inappropriate experimental procedure and conditions, such as irradiation exposure time or intensity, the method of measurement of blood pressure, localization of irradiation, and the initial state of the organism, etc.

Fukalova, in our laboratory, demonstrated that long-term exposure to SW and USW (39 mc and 69 mc) intensities that did not produce any thermal effect induced a persistent depression of blood pressure in rats, preceded by a hypertensive phase.

In detailed experiments Subbota (1957) noted that of the variations in respiration, pulse and blood pressure of dogs exposed in short-term experiments to high irradiation intensities (200—300 mW/cm^2), the blood pressure was the stablest parameter. Other experimental animals (cats and rabbits) were killed by such intensities. With intensities subthreshold for the heating effect (10 mW/cm^2) no changes in the cardiovascular system appeared.

Experiments on narcotized or vagotomized animals led to the conclusion that the changes in respiration, pulse and blood pressure at high intensities were due largely to direct effects of the microwaves on the cerebral cortex and the vagus nerves, or to reflex reactions in the case of local irradiation.

According to Schliephake (1962), microwaves stimulate skin receptors and produce reflex dilatation of deep-seated vessels.

Obrosov, Skurikhina and Safaulina (1963) irradiated healthy human subjects in the cardiac region and plantar surface with microwaves of considerable intensity. Their observations agreed with those of other workers and included improved blood circulation, depression of blood pressure, lowered respiratory rate, slowing of atrioventricular conduction, etc.; irradiation of the plantar surfaces reduced the blood pressure and improved blood circulation in the irradiated and apposing areas. The observed changes were attributed to reflexes and local processes.

The above data, although valuable, do not furnish an answer to the very important question whether SHF electromagnetic fields can produce changes in the cardiovascular system, including hypotension, under industrial conditions, i.e., upon long-term exposure to low intensities.

The state of the cardiovascular system in personnel exposed to SHF fields has been investigated by staff of the clinic of our institute (Kevork'yan, 1948; Merkova, 1949; Orlova, 1960) and also by Uspenskaya (1959, 1961), Tyagin (1962), Gembitskii (1962), Gur'ev (1962) and others. Personnel exposed periodically to SHF irradiation of intensity 1 mW/cm^2 and higher

($3-10$ mW/cm^2) often have *bradycardia and arterial hypotension, sinus arrhythmia or prolongation of cardiac conduction.*

Experimental investigation in animals was required to determine in which degree the change of blood pressure is a specific reaction to low-intensity microwaves of different ranges.

To this end we carried out several series of experiments on 220 rats subjected for long periods to several SHF ranges of different intensities, using Kogan's (1959) plethysmometer for measurement of blood pressure. The initial level of the blood pressure was determined over a period of 2—3 mon and involved 16—25 measurements per animal. The pressure was then measured every 1—3 days in the first mon of irradiation and every two weeks from the second month. Measurements were continued for 2—10 weeks after termination of irradiation in order to follow the recovery process.

Animals were kept in the laboratory for 1—1.5 hr prior to the measurement and parallel determinations were performed on the test and control group.

The millimeter, centimeter, and decimeter ranges were investigated, and the centimeter waves were differentiated into two subranges of 3 and 10-cm waves. Experiments in the subrange of 10-cm waves included also a continuous radiation regime. The animals were subjected mostly to long-term exposure of low irradiation intensities which did not raise the body temperature.

During the 2—3 mon before irradiation, the mean systolic pressure was fairly constant, within 80—90 mm Hg, which is within the normal fluctuation limits according to Kogan and others. The results of blood pressure measurements are summarized in Table 13 and graphs reproduced in Figures 5—9 (abscissae, time and ordinates, % change in blood pressure). Limits of normal variation in the control group are marked by the shaded bar. Each point on the graph is an arithmetic mean of 10—12 measurements.

TABLE 13. Variation of arterial pressure in irradiated rats

Wave range	Irradiation intensity, mW/cm^2	Phase I (rise of pressure)		Phase II (fall of pressure)	
		mean pressure increment, mm Hg	statistical significance	mean pressure decrement, mm Hg	statistical significance
Millimeter	10	—		18.7	$p < 0.01$
	40	22.9	$p < 0.01$	19.14	$p < 0.01$
3-cm	10	—		23.0	$p < 0.01$
	100	10.0	$p < 0.01$	25.2	$p < 0.01$
10-cm (pulsed)	1	12.7	$0.02 > p > 0.01$	14.7	$p < 0.01$
					—
			$0.02 > p > 0.01$	9.4	$p < 0.01$
	10	8.4	$p > 0.01$	—	
10-cm (continuous generation)	10	—	—	8.1	$p < 0.01$
Decimeter	1	—		7.2	$p < 0.01$
	10	7.9	$p < 0.01$	17.5	$p = 0.01$

The mean values of arterial pressure listed in the table show a statistically significant hypotension ($p \leq 0.01$ or $0.02 > P > 0.01$) in experiments with long-term exposure to microwaves of different intensities. The fall in blood pressure is often preceded by a statistically significant hypertension at intensities 40—100 mW/cm^2 in all the ranges, at 10 and 1 mW/cm^2 in the 10-cm range and at 10 mW/cm^2 in the decimeter range.

The variation of blood pressure over the exposure period investigated is traced in Figure 5.

For blood pressure upon exposure to millimeter waves of high (40 mW/cm^2) and low (up to 10 mW/cm^2) intensities see Figure 5.

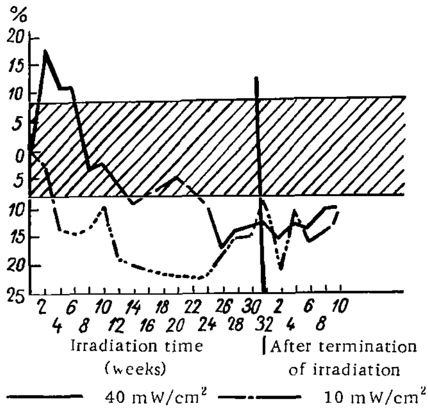

FIGURE 5. Variation of blood pressure upon exposure to millimeter waves

The first period of high-intensity irradiation raised the blood pressure somewhat, followed by a gradual fall from the 14th week to 17% below normal by the 26th week. A somewhat different picture was observed with irradiation intensity 10 mW/cm^2, for which the blood pressure decreased gradually and nonuniformly after the 4th week to reach 20% by the 12th—14th week.*

Results of irradiation with 3-cm waves of intensities 100 and 10 mW/cm^2 are shown in Figure 6. The high irradiation intensity (100 mW/cm^2) produced a two-phase reaction consisting of an initial rise followed by a gradual fall from the 8th week to a minimum pressure in the 12th week of irradiation. Upon irradiation with intensity 10 mW/cm^2 the blood pressure fell in the 6th week without a preliminary rise and reached its minimum in the 12th week (a total change of 25%). The initial pressure was not regained even 8 weeks after termination of irradiation.

The development of hypotension upon exposure to both millimeter and 3-cm waves of low intensities (10 mW/cm^2) occurred after 4—6 weeks of irradiation.

Similar effects of the two ranges were also produced at high intensities, and involved in general a small and unstable rise of blood pressure followed

* The variation of blood pressure is depicted for bi-weekly intervals except in the 16th, 18th, and 22nd weeks, during which no measurements could be performed for technical reasons (dotted line).

by a persistent fall. The only notable difference was a time lag of the hypotensive effect for the millimeter as compared to the centimeter range. The difference was due possibly to a different PFD used (40 and 100 mW/cm^2) as a result of technical characteristics of the generators.

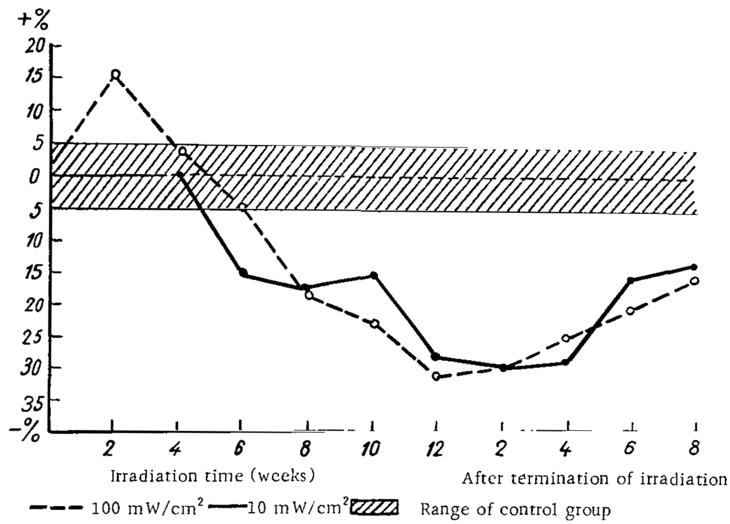

FIGURE 6. Variation of blood pressure upon exposure to 3-cm waves

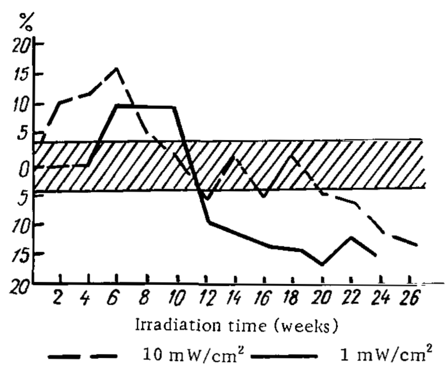

FIGURE 7. Variation of blood pressure upon exposure to 10-cm waves

The effect of 10-cm waves was investigated with irradiation intensities of 1 and 10 mW/cm^2.

The vascular reaction to this wave range proceeded with the familiar two phases (Figure 7). The rising phase was more pronounced and occurred earlier with the higher intensity 10 mW/cm^2; it lasted for 8 weeks and the hypotensive effect appeared only in the 22nd week, reaching a maximum in the 26th week. By contrast, the hypotensive effect was more pronounced with the lower intensity (1 mW/cm^2) and occurred in the 12th week. It was also preceded by a moderate hypertensive phase.

Hence, 10-cm waves produced a hypotension at intensities regarded as low for experimental conditions (1 mW/cm^2) but which may be encountered under industrial conditions.

Figure 8 shows the variation of blood pressure upon exposure to 10-cm waves (10 mW/cm^2), both pulsed and continuous.

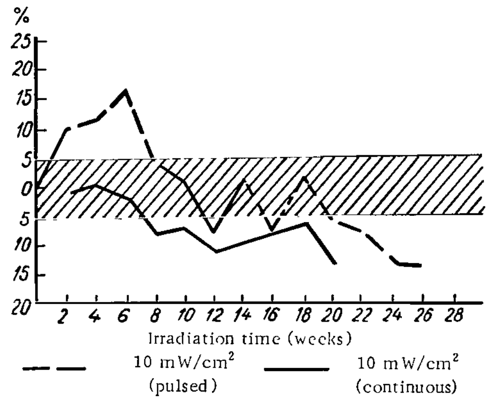

FIGURE 8. Variation of blood pressure upon exposure to pulsed and continuously generated 10-cm waves

The data show that the hypotensive effect occurred earlier (in the 8th week) for the continuous irradiation and the most pronounced statistically significant decrease ($p < 0.01$) occurred in the 20th week. In contrast to the effect of pulsed waves, the fall of blood pressure was not preceded by a rise.

It is difficult to compare our data with those reported by Abrikosov because of the different experimental procedures in respect to the wave ranges, intensities and exposure times. Nevertheless, the difference in response to pulsed and continuous radiations was observed in experiments with both SHF and UHF fields.

Studies of the effect of decimeter waves were performed with irradiation intensities 1 and 10 mW/cm^2. They revealed a statistically significant fall of the blood pressure level (Figure 9).

The figure reveals a transient rise of blood pressure in the first days of irradiation with intensity 10 mW/cm^2. Hypotension appeared in the 10th week and became especially pronounced in the 20th—22nd weeks. The lower irradiation intensity (1 mW/cm^2) produced a hypotensive effect only in the 20th week.

Analysis of the data demonstrated that long-term exposure to all microwaves produced hypotension but the strength, response time and nature of the vascular reaction was dependent upon the particular range and intensity.

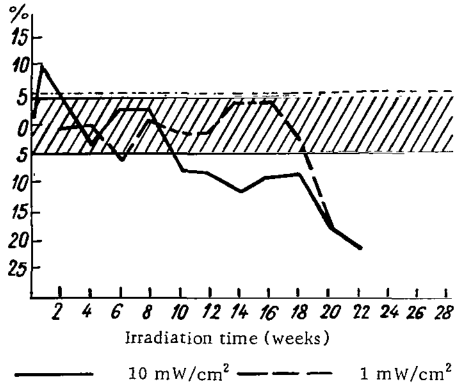

FIGURE 9. Variation of blood pressure upon exposure to decimeter waves

With low irradiation intensities the most pronounced and earliest effect occurred for millimeter and 3-cm waves, which is in agreement with data on personnel working with sources of millimeter waves (Orlova, 1959). There was a typical biphasic response to exposure at high intensities for all wave ranges, and also for low intensities of centimeter and decimeter (especially 10-cm) waves. A statistically significant hypotensive effect was observed at all wavelengths, for intensity 10 mW/cm^2. When superimposed on a hypertensive phase the hypotensive effect appeared later than in the absence of an initial phase (Table 14).

TABLE 14. Time of occurrence of hypotension in rats exposed to low irradiation intensity

Wave range	PFD, mW/cm^2	Hypertensive phase	Onset of hypotension, weeks	Time of occurrence of maximal hypotension, weeks	Fall of pressure, %
Millimeter	10	Not detected	4	24	20
3-cm	10	Same	6	12	25
10-cm	10	Prolonged	22	26	11
Decimeter	10	Brief	10	22	17

TABLE 15. Time of occurrence of hypotension in rats exposed to high irradiation intensity

Wave range	PFD, mW/cm^2	Hypertensive phase	Onset of hypotension, weeks	Time of occurrence of maximal hypotension, weeks	Fall of pressure, %
3-cm	100	Present	8	12	24
Millimeter	40	"	14	24	17

Table 15 describes the vascular reaction to high irradiation intensities (40—100 mW/cm^2), the shortest waves used by us.

The ultimate hypotensive effect was identical for continuous and pulse-modulated 10-cm waves, but the latter induced a two-phase reaction, which was possibly responsible for the later onset of the fall in pressure in this case (Table 16).

TABLE 16. Variation of arterial pressure in rats exposed to pulsed or continuous waves

Wave range	Radiation regime	PFD, mW/cm^2	Hypertensive phase	Onset of hypotension, weeks	Time of occurrence of maximal hypotension, weeks	Fall of pressure, %
10-cm	Pulse	10	Present	22	26	11
Same	Continuous	10	Not detected	8	26	12

Termination of irradiation allowed a slow recovery of the blood pressure to its initial level, after 8—10 weeks.

Having elucidated the characteristics of the variation in blood pressure upon exposure to microwaves, we must now turn our attention to the pathogenesis of the phenomenon.

The blood pressure is regulated by a complex interaction of the sympathetic and the parasympathetic divisions of the autonomic nervous system, which is in turn under the influence of the cerebral cortex.

The major obvious effects of doses insufficient to overheat the animal are the functional changes in the CNS. A change in the functional capacity of the cerebral cortex may alter its regulation of the subcortical autonomic centers and so affect the blood pressure.

In addition to disturbances of cerebral and autonomic regulation, stimulation of receptors in different reflexogenic zones (skin, arcus aortae, myocardium), may also affect the blood pressure.

The pronounced and early hypotensive effect of millimeter waves together with morphological confirmation indeed prove that these microwaves affect skin receptors. Further morphological tests demonstrate vascular disturbances and dystrophic changes, especially in the thalamo-hypothalamic region, which participates in the regulation of vascular tonus.

Finally one must recognize the possibility of a humoral mechanism of the change in blood pressure. This is suggested by some of our results which pointed to a lowered cholinesterase activity in the blood serum and organs of irradiated animals (Nikogosyan, 1960, 1963). These data imply a rise of blood acetylcholine and an effect on autonomic control in the organism.

It is known that K and Ca in the blood regulate autonomic function and may also affect the blood pressure. Komendantova (1959) demonstrated that blood pressure could depend on the concentration of Ca salts in the blood serum. Preliminary data of ours indicate an increased consumption of Ca and K salts by animals subjected to long-term irradiation with microwaves of high intensity (Kulakova, 1962, 1964).

The hypotensive effect apparently results from a complex process of neural disturbance, the exact nature of which depends on the wave range. Millimeter waves, which are completely absorbed by the skin, affect sensory receptors and cause reflex effects. The longer decimeter range of microwaves is scarcely absorbed in the skin but penetrates deeper and seems to have a direct influence on autonomic centers. Humoral influences cannot be excluded.

Detailed comprehensive research into the biophysical, physiological, biochemical and morphological aspects of the changes is required to elucidate the mechanism of the hypotensive effect.

One may summarize the data given above as follows:

1. Long-term exposure to SHF fields (millimeter, centimeter and decimeter waves) causes a specific hypotensive effect both for high and low irradiation intensities.

2. The strength and time of occurrence of the effect depend upon irradia tion intensity and wave range. For the same irradiation intensity (10 mW/cm^2), the most pronounced and earliest hypotension is produced by millimeter and 3-cm waves.

3. With high intensities of all ranges and low intensities of decimeter and 10-cm waves the response is biphasic, involving an initial rise followed by a fall in blood pressure.

4. The mode of generation of SHF energy (pulsed or continuous) does not affect the ultimate degree of hypotension due to the microwave irradiation.

5. The blood pressure level returns to normal in the 8th—10th week after termination of irradiation which indicates reversibility of the induced processes.

6. The hypotensive effect of microwaves is probably due to a complex disturbance of neural regulation, resulting from a direct effect on the nerve centers, as well as reflex and humoral processes.

Effect of microwaves on certain functions of the nervous system in experimental animals

Clinical observations show that the human nervous system responds to low-intensity radio waves with several nonspecific reactions, mainly in the higher divisions of the CNS, and marked asthenia.

The effect of radiowaves on the nervous system of experimental anima has been very little studied for the long and medium range, closer attentio having been paid to the ultrashort and recently to the microwave range.

Both high and low intensities affect the animals' conditioned reflexes and bioelectric activity of the cerebral cortex, etc. The nature and the degree of change depend upon the intensity, exposure time, wave range, localization of irradiation and typological traits of the animals.

Nikonova (1963) investigated the influence of electric and magnetic components of medium waves on training time of the conditioned motor-alimentary reflex in rats. According to Golubev (1958) and Grigor'ev (1960), conditioned reflexes are more sensitive to external influences in the course of training than when already fixed.

Nikonova could not observe any marked influence of the electric (1,800 V/m) or magnetic (50 amp/m) components of the field on the training time in the rats. She did report a more rapid decrease in the latent period of the motor reaction during training, especially with the electric field and this suggested enhanced excitability of the animals' CNS. Electromagnetic fields of the same frequency and force (1,000 V/m and 50 amp/m) increased the amplitude of the cerebral cortex biopotentials in rabbits after a 10-min exposure.

Hence, medium waves of even considerable intensity produced only small functional changes in the CNS.

We are acquainted with five papers dealing with the effect of UHF fields on conditioned reflexes in animals (Kharchenko, 1939; Glezer, 1940; Promtova, 1956; Livshits, 1957; Baronenko and Timofeeva, 1959). Although these investigations were performed on different animals (pigeons, rabbits and dogs) and under incomparable and not always stated conditions of irradiation intensity, wavelength, exposure time and localization, they all suggest changes in the conditioned reflexes of animals under the influence of UHF.

Upon irradiation of a pigeon's head for 3—5 min (generator power 35—300 W), Kharchenko noted changes ranging from substantial protraction of the latent period in motor alimentary conditioned reflexes to total disappearance of positive conditioned reflexes.

Glezer observed a weakening of internal inhibition in the cerebral cortex and loss of the power of discrimination in a dog whose head was exposed to a UHF field (evidently of low strength, judging from the animal's behavior).

Promtova conducted multiple exposures of dog's heads to UHF fields and revealed phase changes in the conditioned reflexes. Cortical excitation marked the first phase and was then followed by appreciable inhibition of cortical functions.

Livshits irradiated various cortical zones of dogs with UHF fields (7—55 W) and could distinguish reversible changes such as diminished positive conditioned reflexes or disturbed discrimination. He established that the cortical reaction was dependent both upon the localization of irradiation and the animals' typological traits. Promtova also noted these properties and paid special attention to their dependence on the initial functional state of the cortex. Baronenko and Timofeeva characterized the changes in animals which were initially in different states of higher nervous activity.

Livshits emphasized the erratic nature of the response, since, after the same dose of UHF waves in different experiments, conditioned reflexes might be either present or absent. Indeed, repeated exposures of dogs' cerebellar areas could both strengthen or weaken conditioned reflexes, so that the resultant effect depended on which of the two trends predominated.

Inhibition of positive conditioned reflexes in rats and rabbits exposed to UHF fields was discovered by Baronenko and Timofeeva. Their experiments were distinguished by more accurate dosing and they demonstrated that daily 2-hr exposures of rabbits to UHF fields (60—200 V/m) produced inhibition of positive conditioned reflexes after 10—30 exposures.

The literature contains but few studies of cortical electric activity under the influence of UHF electromagnetic waves.

In one such study Pardzhanadze (1954) exposed rabbits to UHF fields and observed rapid waves of the highest amplitude in the EEG after irradiation.

Kholodov and Yanson (1962) noted effects of UHF fields on rabbit EEG's. In 81% of all cases an increase in current amplitude and a decrease in frequency occurred, but in 19% of cases a decrease in amplitude and an increase in frequency was noted. The latter reaction was related by the authors to the painful effect of the UHF field in some experiments. The reproducibility of reaction (percentage ratio of the number of responses to the number of exposures) rose with increasing strength of the electromagnetic field (within the limits of 1,000 — 5,000 V/m). The authors showed increasing excitability of the cortical terminus of the visual analyser in an UHF field of 1,000 V/m, and it persisted for several minutes after termination of exposure.

Investigations into the conditioned reflexes of animals exposed to the SHF range (microwaves) are also few in number. Mention may be made of the work of Subbota (1957, 1962), Lobanova (1959, 1964), Lobanova and Tolgskaya (1960), Gorodetskaya (1960), Svetlova (1962) and Minecki et al. (1962).

In experiments on dogs, Subbota demonstrated (1958) that excitation was enhanced by a single exposure to weak SHF fields. Multiple exposure produced phase phenomena and increased successive inhibition. Strong SHF fields diminished the magnitude of conditioned reflexes and disinhibition of discrimination, weakening both the excitation and inhibition process. Decimeter waves produced more marked and persistent changes in comparison to centimeter waves.

Svetlova (1962) irradiated dogs with decimeter waves of low intensities (2 mW/cm^2) and observed an asymmetric response, whereby inhibition of positive conditioned reflexes occurred on the irrradiated side and a slight strengthening on the nonirradiated side. The asymmetry persisted during more prolonged irradiation (for 1 — 3 mon) and repeated treatments caused erratic changes in the dogs' conditioned reflexes, with disturbance of the strength relationships in the form of equality, paradoxical and ultraparadoxical phases.

The conditioned reflexes of mice subjected to a single exposure of high intensity 3-cm waves were studied by Gorodetskaya (1960). On the day after irradiation this author could identify changes in the magnitude of conditioned reflexes to light and the ring of a bell, disinhibition of discrimination, and a disturbance of strength relationships in the cerebral cortex. The conditioned reflexes were normal 7 — 10 days after irradiation. Minecki et al. (1962) examined rats irradiated with centimeter waves of intensities within 16 — 94 mW/cm^2 and exposures ranging from a few seconds to 35 min. They reported an initial strengthening of excitation, for all combinations of irradiation intensity and duration, followed by a decrease of excitability and successive inhibition upon more prolonged irradiation.

These authors correlated the changes in the conditioned reflexes with a parallel rise in the body temperature. The first manifestations of excitation were observed when the body temperature had risen by 0.6 — 1.0°C, while successive inhibition was accompanied by a rise of 3.0 — 3.5°C. The authors also allowed for the possibility of nonthermal effects.

Most of these investigations into the cortical bioelectric activity have been carried out with high irradiation intensities.

Bychkov (1957), for example, noticed variations in the cerebral bioelectric activity of rabbits and cats following unilateral irradiation with

PFD 100 and 20 mW/cm^2. 100 mW/cm^2 caused depression of the dominant rhythms, appearance of slow waves and hemispheral asymmetry in the EEG. Stimulation of biopotentials was induced by lower intensities (20 mW/cm^2), by diminished exposure and isolated irradiation of the body trunk. The author's results led him to infer a parabiotic mechanism of the effect of SHF on the CNS. The nature of the hemispheral asymmetries in consequence of various local irradiations implied the presence of both direct (dominant) and reflex effects of SHF fields on the CNS.

Still higher SHF intensities (1,000 — 300 mW/cm^2) were used by Bavro and Kholodov (1962), but in contrast to Bychkov they recorded the rabbits' EEG simultaneously with irradiation. In response to the SHF field the rabbits and cats displayed slow high-amplitude oscillations in the visual cortex and high-amplitude spindles in the frontal cortex, persistent after termination of irradiation. When CNS excitability was heightened by administration of caffeine, the SHF field produced "spasmodic discharges" in the cortex and general spasms (89% of the cases). After mechanical injury to the cortical area, the SHF field provoked spasmodic discharges in 80% of cases, and both light (60%) or sound (40% of cases) could also induce the phenomenon.

Baldwin et al. (1960) experimented with high-intensity decimeter waves. A 2–10-min exposure of macaques brought about the appearance of slow waves in their EEG whose origin, according to the authors, lay in the mesencephalon and diencephalon.

The literature dealing with EEG studies and the effect of low-intensity microwaves on the CNS is very limited. Of the three papers known to us, two deal with investigation of human subjects. Sinisi (1954) applied microwaves (radar) to human subjects therapeutically, and while he was unable to detect any change of EEG in the majority of cases, in certain instances an increased amplitude of biopotentials with simultaneous flares of slow theta activity were apparent.

According to Bychkov (1962), any human EEG variations under the influence of low-intensity SHF fields are merely manifestations of the general asthenia.

Kholodov demonstrated (1962) that decimeter waves of intensities 2, 10 and 50 mW/cm^2 often produced slow high-amplitude oscillations in rabbits' EEG. The reproducibility of this reaction rises with increasing PFD and after cerebrotomy. Discharges of the strychnine type may be produced by this type of irradiation in an isolated brain, and the response persists after destruction of distant analysers. The SHF field was concluded to exercise a direct effect on the diencephalon and prosencephalon.

The effect of microwaves on the state of animals' nervous system has been investigated in our laboratory over a period of several years with emphasis on conditioned reflexes, subjection to sound stimuli, EEG, etc.

On keeping with past practice, our studies on conditioned reflexes were performed with mainly low-intensity microwaves (up to 10 mW/cm^2). Long-term experiments involving 2 — 6 months' irradiation were carried out by Lobanova, mostly on rats, utilizing motor-alimentary methods. The conditioned reflex was trained to sound and light stimuli of various strengths.

In general the overall effect of microwaves of any range is the weakening of excitation and growing protective inhibition in the CNS (increase in the latent period of conditioned reflexes, disturbance of strength relationships in the cerebral cortex, loss of conditioned reflexes), in spite of exceptions in individual animals. The disturbances in animals' conditioned reflexes develop in degree and kind according to the microwave range.

Like other responses, those of the CNS of animals exposed to microwaves often show two phases.

In the millimeter and decimeter wave ranges (PFD $= 10$ mW/cm^2) the first phase is characterized by enhanced excitability and weakened active inhibition during the first two months of irradiation, while the second phase is typified by the development of protective inhibition in the 3rd—4th mon. The effect on animals' conditioned reflexes was more pronounced for decimeter than for millimeter waves.

After irradiation (5—7 times) with 10-cm waves of the same intensity as millimeter and decimeter waves, the changes typical of the first phase were observed only in some animals. Other animals exhibited an inhibition of conditioned reflexes from the first days, progressing with an increasing number of irradiation sessions. As a rule the animals' conditioned reflexes returned to normal two months after termination of exposure.

Morphological investigations after exposure to microwaves revealed alterations in the interneuron axodendral and axosomatic connections of the cerebral cortex. These changes were reversible and disappeared 3—6 weeks after termination of exposure, in parallel with recovery of the animals' conditioned reflexes.

The use of animals which are highly susceptible to sound stimuli and which respond to a bell with specific motor reactions and spasmodic cerebral attacks of varying intensity has enabled many investigators to study the effect of various agents on the CNS.

This reaction, first reported by Studentsov in 1922 and described by Vasil'ev (1924) in Pavlov's laboratory, was analyzed physiologically by Krushinskii at a considerably later date (1950, 1960). The sound stimulus induces, specifically, one or two waves of motor excitation and may terminate in a spasmodic attack. According to Krushinskii, the intensity and nature of the reaction are controlled by the excitation/inhibition ratio. Characteristic indicators of the response in a population of rats susceptible to the stimulus are the duration of the latent period and first excitation wave, the force of the attack, the nature of the reaction (1 or 2 waves) and the duration of the pause between the two excitation waves. The last parameter characterizes the state of inhibition to a certain extent.

Animals susceptible to the sound stimulus were of special interest to us because of their higher state of excitability, which constitutes a precondition giving rise to more pronounced and earlier responses to irradiation.

The investigations were carried out in our laboratory by Kitsovskaya (1960, 1964) using irradiation intensities up to 10 mW/cm^2.

The data in Table 17 demonstrate the same trend of reaction for all ranges at the same intensity, but there are also certain peculiarities depending upon the wave range.

Abnormalities were more frequent in the 10-cm range and tended to involve lower reaction strengths.

A similar picture was obtained also for the decimeter range, although in a somewhat smaller percentage of cases. However, the decrease of sensitivity in this range occurred earlier and was more persistent.

Response was less frequent for the 3-cm and millimeter ranges but if apparent, it too was typified by a reduction in sensitivity after an initial erratic period.

An increase of the latent period was pronounced in all the microwave ranges. In addition to a decreased strength of response and an increased latent period irradiation also increased the duration of the first excitation wave and shortened the inhibition period between the two excitation waves.

These changes indicate that both excitation and inhibition are affected by irradiation with microwaves of different ranges. The differences between the microwave ranges manifest themselves in the time of occurrence of the changes, their strength and persistence. The most pronounced, earliest and persistent changes were produced by decimeter waves, followed by 10-cm and finally by 3-cm and millimeter waves.

TABLE 17. Response to microwave irradiation of rats susceptible to sonic stimulus

Microwave range	Cases of modified reactions, %	Nature of modification of reaction	Time of occurrence of modification (irradiation sessions)	Increase of latent period (irradiation sessions)	Recovery time
Decimeter	84.3	Decrease	1–4	30	> 5 mon
Centimeter:					
10 cm	100	"	23–25	40	19–20 days
3 cm	58.4	"	40	100	19–20 "
Millimeter	50	Erratic	50	150	19–20 "

The CNS disturbances resulting from long-term exposure to microwaves which were described above apparently represent the cumulative effects of single exposures to low irradiation intensities. It was suggested that application of delicate techniques might reveal early changes in the state of the CNS.

Sensitivity of the nervous system to low-intensity microwaves and the early physiological changes (which are successfully compensated by the organism) were investigated by EEG studies of the cortical electric activity (research carried out by our laboratory in collaboration with a group of Prof. N. M. Livanov's colleagues). Rabbits (320 animals) were exposed to whole-body irradiation with centimeter and decimeter waves (continuous generation and pulse modulation) of intensities varying between 50 and 0.02 mW/cm^2. The EEG was recorded for 13 min (3 min before irradiation, 5 min during irradiation and 5 min after irradiation) with a four-channel electroencephalograph 4-EEG-1.

Determination of mean latent periods and of the strength and reproducibility of the response made it possible to assess the sensitivity of the CNS to microwaves.

Fluctuations in the cerebral biopotentials during irradiation were the same as those occurring "spontaneously" in normal animals. The most frequent variation due to irradiation was the frequency-amplitude characteristics of the EEG. Activity different in type to the initial EEG was rare. The reproducibility of the response to irradiation rose as the intensity increased from 0.02 to 50 mW/cm^2. The mean latent periods of EEG changes diminished with increasing intensity. Analysis of the relationship between intensity and the duration of latent periods permitted construction of strength-duration curves for the different wave ranges (Figure 10). As can be seen, the curve of the CNS sensitivity to microwaves was closely similar to the Goorweg-Weiss sensitivity curve for electric current and Tsypin-Grigor'ev curve (1960) for ionizing radiations.

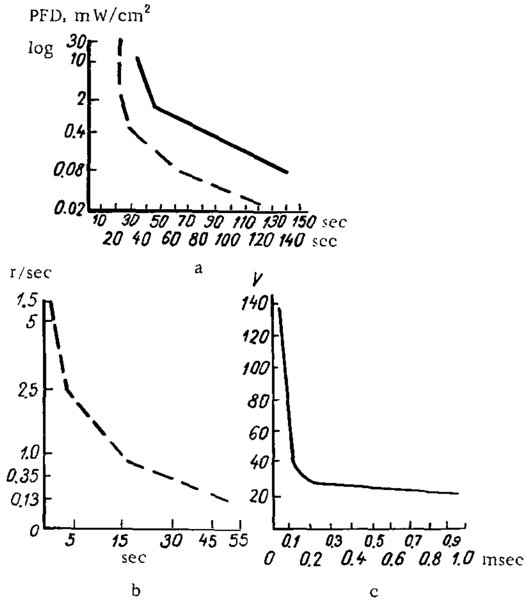

FIGURE 10. CNS strength-duration curves:

Solid line — millimeter range; dashed line — decimeter range.

a — sensitivity to radiowaves; b — to ionizing radiation; c — to electric current.

Experiments on intact rabbit and isolated brain (after cerebrotomy at the level of mesencephalon) revealed that the latter reacted to irradiation more frequently and strongly than the intact brain. The drastic curtailment of afferent information arriving at the frontal parts of the brain isolated from the underlying divisions, as well as the disturbance in the cerebral blood supply following cerebrotomy, probably reduced the compensatory capacities of the CNS quite radically. Cerebrotomy constitutes a crude derangement of neural compensatory mechanisms and is itself a strong positive stimulus for the frontal parts of the brain; it also eliminates the inhibitory effect of afferent impulses. Administration of caffeine also increases the brain's sensitivity to microwaves.

Having obtained some idea of the sensitivity of the CNS to microwaves it was necessary to embark on investigations of the dynamics of the variations upon prolonged exposure.

Although research in this direction has only just begun in our laboratory, it may already be stated that irradiation for 1 — 2 mon with intensities which do not produce an overall heating effect may produce functional changes in the CNS. The changes include modified reactivity of the CNS to certain stimuli (rhythmic light) and a propensity to epilepsy in some experimental animals; on sensory provocation (photostimulation) this propensity frequently manifests itself in epileptiform bioelectric activity (Figure 11).

Such paroxysmal bioelectric activity upon sensory provocation following irradiation was observed in 7 out of 12 experimental animals. The fact that irradiation can itself provoke epileptoform activity, in addition to obliteration or appearance of hemispherical asymmetries, suggests that every irradiation session constitutes a considerable stress on the CNS.

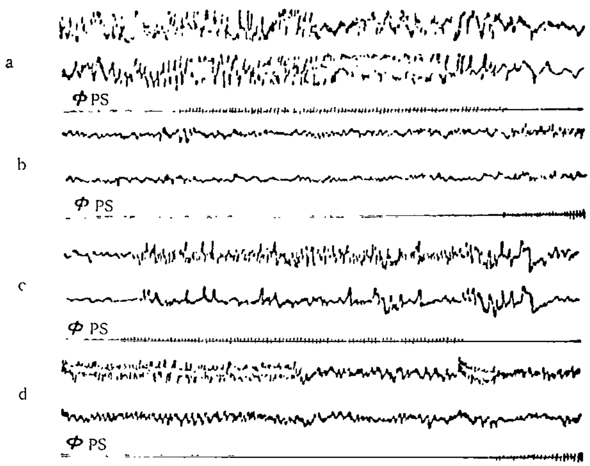

FIGURE 11. Variation in the reactivity of the CNS to rhythmic light stimulus upon exposure to decimeter electromagnetic waves:

a, b — different forms of epileptoid bioelectric activity in photostimulated rabbits previously subjected to 2 months' irradiation; c — EEG of rabbit; d — post-irradiation. PS — photostimulation mark.

Electroencephalographic investigations of human subjects exposed to long-term irradiation were carried out in the Institute's clinic (Drogichina et al., 1962; Ginzburg and Sadchikova, 1964) and revealed significant EEG changes,particularly paroxysmal groups of slow waves, mostly of the theta range. It is suggested that subcortical structures, including the diencephalon, are responsible for manifestation of paroxysmal bioelectric activity observed in human subjects and in experimental animals.

Hence the results of the EEG investigations revealed a marginal reaction of the CNS to microwaves. The sensitivity of the CNS in animals rises upon increasing the irradiation intensity, and also after cerebrotomy or administration of caffeine. Changes in cerebral activity are more pronounced and occur earlier with decimeter waves compared to 10-cm waves.

The variety of techniques used to detect changes in the CNS produced by irradiation is complemented by biochemical methods (Nikogosyan).

Cholinesterase plays an important role in transmission of nervous impulses. Following multiple irradiations with low-intensity microwaves (up to 10 mW/cm^2) cholinesterase activity in the blood serum and liver, heart and especially the brain stem of rabbits and rats is reduced. The decrease of cholinesterase activity occurred first in the blood serum, then in the brain stem and finally in the other organs.

The degree of the effect on cholinesterase activity, its incidence and time of occurrence depends on the microwave range.

The most marked and early decrease of cholinesterase activity in both the blood serum (after 10—20 sessions) and brain stem (after 24 sessions) occurred with the decimeter waves. Ten-centimeter waves produced changes in 70% of the cases (after 30—40 irradiation sessions).

The effect of millimeter waves was considerably weaker. The decrease in cholinesterase activity was mild and manifested itself only after 180 irradiation sessions; it occurred in a smaller percentage of cases (63%) and was limited to the blood serum and brain stem. The decrease in activity was preceded by some increase in the brain stem.

Cholinesterase activity returned to normal 30—45 days after termination of irradiation.

In this connection, significant data were reported by Bychkov and Syngaevskaya (1962) who pointed out the important role of cholinergic processes in the mechanism of the nonthermal effect of the SHF field.

Morphological changes in animals irradiated with microwaves

We shall now review the most significant work on morphological changes in animals irradiated with different ranges of radiowaves.

We have been unable to find any papers in the available literature dealing with the effects of medium radiowaves. Investigations carried out in our laboratory (Nikonova, 1963) revealed that long-term exposure (10 months) of animals to medium radiowaves with comparatively weak fields (electric field of 1,800 V/m, magnetic field of 50 amp/m) produced moderate histological changes in the tissues and organs. They included abnormalities in the receptors and synapses of the nervous system, moderate vascular disturbances, a proliferate reaction of the reticuloendothelial system and initial dystrophic changes in the cerebral cells and those of internal organs.

A considerable number of papers have been devoted to morphological examinations of the organs and tissues of animals exposed to short and especially ultrashort waves (SW and USW) of high intensities.

The majority of authors have described a similar picture of the effects in the organs and tissues of animals exposed to doses causing overheating. Mice, rats and rabbits used in short-term experiments perished rapidly with marked signs of overheating (Shibkova, 1937; Vorotilkin, 1940; Zhukhin, 1938). According to Slavskii and Burnaz (1933) death is most probably caused by cardioplegia, which is masked by rapid rigor mortis of the myocardium.

Exposure of animals to lethal doses of USW and SW produced venous hyperemia in the brain and internal organs and multiple hemorrhages of the pleura, pericardium and meninges. According to Zhukhin and several other workers, heavy doses of USW and SW produce hyperemia and hemorrhages in all the internal organs and the brain, dystrophic disturbances of the myocardium, cells of parenchymatose organs, various divisions of the CNS, vegetative ganglia, synapses and mobilization of reticuloendothelial elements in general, especially in the brain.

A group of papers has been devoted to the effect of moderate thermally ineffective doses (Rakhmanov, 1940; Militsin and Voznaya, 1937; Slavskii and Burnaz, 1933 and many others). Morphological changes reported in these papers included swelling of vascular endothelia, especially capillaries of the liver and the renal tubules, splenic irritation (mytosis, plasmocytes) and stimulation of the hematopoietic function, etc., indicating participation of the reticuloendothelial system in the overall reaction to SW and USW. According to certain investigators (Broderzon and Fandrei, 1939; Derevyagin, 1939), the functioning of the reticuloendothelial system is inhibited by USW, but the discrepancies may have stemmed from differences in the experimental procedures (intensity and duration of irradiation, animal species, etc.).

Several papers have described endocrine effects of SW and USW.

Oettingen (1931), Lotis (1936), Gillerson and Voznaya (1939) described the effects of SW and USW on the gonads. The morphological change in ovaries included abnormalities of the ova, presence of atresic follicules beside normal ones and occasionally disappearance of chromatin structures in the nucleus. These authors emphasized that the changes became reversible 20—22 days after termination of the irradiation.

The morphological disturbances in testes range from slight modifications to necrosis (Schliephake, 1932; Oettingen, 1931), depending upon the duration and intensity of irradiation. Tissue hyperemia, hemorrhages and shrivelling of sperm ductules without disturbance of spermatogenesis are typical. More drastic effects may include complete necrosis of tissues and disturbance of spermatogenesis. Alekseenko (1940), Berdichevskii (1940) and Vorotilkin (1950) discovered degenerative changes in endocrine glands upon multiple UHF irradiation.

Certain features of morphological changes following irradiation are clear from the investigations described above. Large doses in short-term experiments produce overheating with characteristic hypothermal morphological changes. Long-term exposures to moderate doses induce certain degenerative processes with vascular disturbances and lesions of vegetative centers and ganglia, accompanied by mobilization of elements of the reticuloendothelial system in general and especially in the brain. Low intensities mostly provoke a moderate proliferative reaction in the reticuloendothelial system.

Investigations carried out in our laboratory (Fukalova) revealed that exposure to extreme doses of USW and SW (5,000 V/m and 9,000 V/m, respectively) produced acute vascular disturbances in all organs and the nervous system (with perivascular and pericellular edema and multiple hemorrhages), droplet lipodystrophy of some hepatic cells, nonuniform stainability of muscle fibers, marked irritation of skin receptors and myocardium interoceptors.

Prolonged multiple irradiation, for as long as 5 mon, with subpyretic USW and SW intensities affected mostly the nervous system, with shrivelling of cortical cells, degeneration of neurons of the thalamo-hypothalamic region and stimulation of the peripheral receptor and interoceptor apparatus. Internal organs exhibited slight dystrophic changes accompanied by proliferative compensatory processes. A characteristic feature was the breakdown of the spermatogenetic epithelium of some seminiferous tubules. Most of the tubules retained their spermatogenetic capacity, and the animals' reproductive power was not affected.

The morphological changes are less pronounced upon exposure to SW.

For the range of microwaves (SHF), the morphological investigations in the literature have been mainly concerned with continuously generated centimeter waves, while few papers have been devoted to the effects of pulsed centimeter waves and to decimeter waves. We have not come across any work on the millimeter range.

Milyutina carried out experiments on mice irradiated with decimeter waves ($\lambda = 40$ cm). Therapeutic doses of decimeter waves did not cause any vascular or cellular effects typical of the thermal reaction to USW. The author reported considerable disturbances in the liver (swelling of the cell protoplasm and turbidity) and in the kidneys (infolding of glomerulae, dilatation of capillaries, swelling and a cloudy appearance of the convoluted tubules' epithelia).

Seguin and Castelain examined the morphology of rats and mice irradiated with decimeter waves ($\lambda = 21$ cm) of different doses, i. e. the animals were irradiated with a constant high intensity for 5 sec, 15 sec until the lethal dose was reached. Weak irradiation for 5 sec raised the rectal temperature by 0.2°C, and in such cases microscopic examination revealed occasional vascular abnormalities in the lungs with slight dilatation of the capillaries but without tissue lesions. More intensive irradiation raised the rectal temperature by 0.8°C and produced considerable vascular dilatations. Marked hemorrhages were observed in pulmonary tissue, spleen and liver. Lethal doses produced numerous pulmonary infarctions, hemorrhages in the liver and kidneys, dilitation of atrium cordis dextrum, which was filled with blood.

Boysen irradiated rabbits (Flemish giants) with radiowaves ($\lambda = 84$ cm) and observed diffuse dystrophic changes in the cerebral cells, epithelial cells of the renal convoluted tubules, moderate dystrophy of myocardial fibers, hepatic cells, gastrointestinal tract and respiratory tract. The changes were persistent and occurred in animals killed by irradiation, or 61 days after irradiation. The author emphasized that irradiation with pulsed and continuous waves produced similar effects.

The above-mentioned investigations cannot unfortunately be easily compared due to the different wavelengths used by the experimenters ($\lambda = 40$, 21 and 84 cm); the irradiation intensities were different in each case but were at any rate fairly high.

A few studies have been carried out on animals irradiated with centimeter waves.

Austin and Horvath (1954) irradiated rats with continuous centimeter waves ($\lambda = 12.2$ cm), apparently of high intensity, and observed a considerable rise of rectal temperature and convulsions when the animal's head only was irradiated. In spite of the pronounced clinical manifestations of the centimeter waves these authors did not, paradoxically, observe any morphological changes.

Extensive studies were carried out by representative of the Kirov Military-Medical Academy (Pervushin and Triumfov (1957), Pervushin (1957), Pitenin (1959, 1962)). Pervushin and Triumfov investigated a large group of rabbits subjected to a single irradiation of lethal intensity or to multiple (long-term) irradiation of high or low intensity. In the single-irradiation experiment the authors observed pronounced vascular disturbances and minor dystrophic changes. In the long-term experiments they noted hyperemia and hemorrhage of various organs, pronounced dystrophic changes including protein dystrophy of renal convoluted tubules' epithelia, hepatic cells, myocardial fibers and perivascular edema. The authors attributed the observed changes to disturbances in the vascular permeability.

Morphological manifestations in the myocardium of rabbits and albino rats irradiated with microwaves were investigated by Pitenin (1959). He demonstrated regular nonspecific vascular and dystrophic myocardial changes, the degree of which was dependent upon the intensity and duration of irradiation and the initial functional state of the body.

Interesting observations on certain divisions of the nervous system involved in cardiac innervation were reported by Pervushin (1957). He found that exposure to a SHF field produced mainly changes in afferent neurons' endings. Effects on cardiac receptors and some cells in sensory ganglia were also observed in conditions precluding any body heating. The author's suggestion that certain pathological reactions are due to the influence of the SHF field on receptors is in agreement with our results showing changes in the afferent links of reflex areas following irradiation.

Dolina (1959) studied histopathological phenomena in structures of various organs and tissues in rats and rabbits irradiated for 10 days with centimeter waves of high (220 – 40 mW/cm^2) or low intensity (a few mW/cm^2).

The authors discovered circulatory disturbances of varying degrees and degeneration of cerebral neurons, autonomic nervous system ganglia and viscera. These effects were thought to be a result of anoxic phenomena in the CNS and reflex disturbances of the central regulation of blood circulation, due to the thermal effect of centimeter waves.

Studies on mice exposed to thermally effective (64; 30.5; 16.5 mW/cm^2) centimeter waves ($\lambda = 12$ cm) were carried out by Minecki and Bilski (1961), who discovered the fastest reaction occurred in connective tissue rich in reticular cells. The formation of infiltrates in viscera and muscles is regarded by the author as a typical result of exposure to microwaves, the liver being especially sensitive to irradiation.

Several investigators have discovered dystrophic changes in the gonads of animals irradiated with high-intensity centimeter waves (Imig, Thomson and Hines, 1948; Gorodetskaya, 1962). Gorodetskaya demonstrated a higher sensitivity of ovaries compared to testes. Gunn, Gould and Anderson (1960) investigated the effect of irradiating centimeter waves ($\lambda = 1.25$ cm) of intensity 250 mW/cm^2 for 15, 10 and 5 sec, on the endocrine system of males. They reported third-degree burns of scrotal skin and hemorrhages in the testes, and microscopic coagulatory necrosis of seminiferous tubules, interstitial and vascular tissue. The testes exhibited a decrease in size 29 days after irradiation. The seminiferous tubules were devoid of germinal epithelium and the interstitial tissue contained numerous fibroblasts but few Leydig's cells. The reaction of the testicular tissues was much less pronounced when the irradiation time was reduced to 10 or 5 sec.

Ummersen (1961) demonstrated that microwave irradiation ($\lambda = 12.25$ cm) of intensity 400 mW/cm^2 inhibited cellular differentiation of the developing chicken embryo. Tissues already differentiating showed cellular proliferation but no further differentiation; development and differentiation in pre-differentiated tissues was altogether prevented. Certain review data were supplied by Boiteau (1960).

The data cited above demonstrate that most investigations were carried out at high intensities and the observed changes were apparently due to the thermal effects of the irradiation. A few authors only have concerned themselves with the effect of comparatively low intensities, but here too the data by no means exclude possible thermal effects. No work at all has been done on the effect of low-intensity millimeter and decimeter waves.

We have undertaken studies of morphological changes in animals following single or multiple irradiation with various ranges of microwaves.*

We aimed at elucidating the general nature of the morphological changes in the various organs and tissues, and specific characteristic and comparative effects produced by the different microwave ranges (Tolgskaya and Gordon, Lobanova, 1955, 1959, 1960; Tolgskaya and Gordon, 1960, 1964). To this end we examined the organs of 211 rabbits, rats and mice irradiated with 10- and 3-cm waves, pulsed millimeter and decimeter waves and with single and multiple irradiation of intensities ranging from 1 to 100 mW/cm^2.

A single irradiation with microwaves (centimeter, millimeter, decimeter waves) of high intensity produced pronounced overheating, accompanied by marked hyperemia, perivascular edema and hemorrhages in the brain and internal organs. We observed, moreover, acute swelling and vacuolization of the protoplasm in the cerebral neurons, lipodystrophy of hepatic cells and protein dystrophy of renal convoluted tubule epithelia. Characteristic features in cases of severe overheating were fragmentation of some myocardium fibers, disintegration or necrosis of some seminiferous tubules and total absence of microglial proliferation in the brain and cells of the reticuloendothelial system of the liver.

Single irradiation of animals with low intensities (up to 10 mW/cm^2) produced only slight vascular disturbances and dystrophic changes in the cells of the brain and parenchymatose organs.

Animals subjected to multiple intense microwave irradiation (40—110 mW/cm^2) exhibited severe clinical phenomena of overheating in the first irradiation sessions. After that the animals tolerated irradiation satisfactorily, their body temperature returned to normal 1—1.5 hr after the termination of irradiation, and the weight increment of young experimental animals was not different from that of the controls. Investigations revealed moderate vascular disturbances and mild dystrophic changes in the nervous system and internal organs. The animals remained practically healthy indicating extensive compensatory processes of the intact organism.

A somewhat more detailed discussion should be provided for long-term irradiation of animals with low-intensity microwaves.

Animals exposed to multiple irradiations of low intensity (up to 10 mW/cm^2) were in a satisfactory general state, but tended to manifest degenerative changes in the nervous system and internal organs accompanied by a small proliferation of the cerebral microglia (Figure 12) and cells of the hepatic reticuloendothelial system (Figure 13).

* The investigations were carried out by M. S. Tolgskaya.

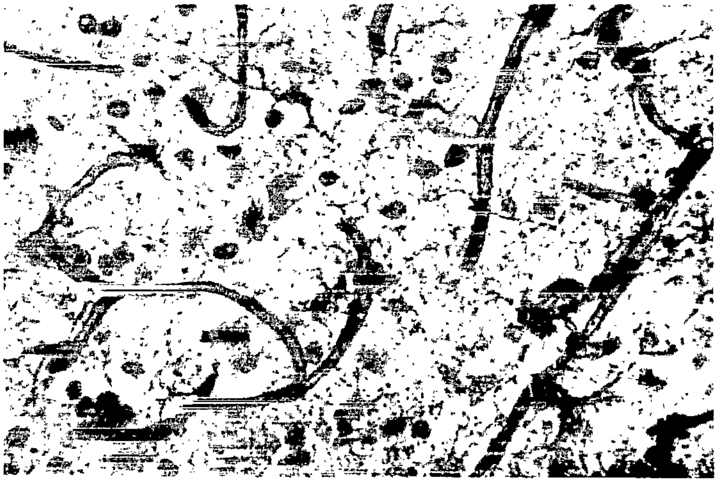

FIGURE 12. Brain. Perivascular proliferation of microglial elements (Miyagawa)

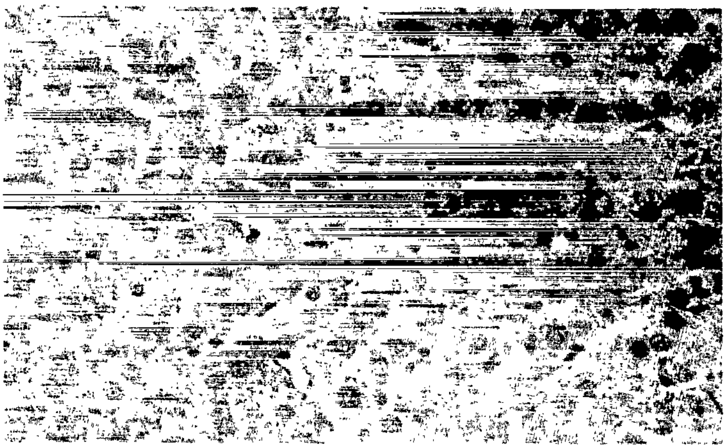

FIGURE 13. Liver. Proliferation of reticuloendothelial elements (hematoxylin-eosin)

The slight distances observed were clearly compensated by the animals which remained healthy. The effects were reversible and were not apparent in animals killed 2—3 weeks after the irradiation was terminated.

In view of the changes in the CNS of irradiated animals, we have used more delicate methods of study of the synaptic and receptor structures of the nervous system.

Recently, Sarkisov (1948), Zurabashvili (1951), Polyakov (1955) and Dolgo-Saburov (1956), in their studies on the changes in the branches of neuron dendrites produced by toxic, traumatic or infectious deleterious agents, found that those branches which constitute a highly differentiated part of the synaptic receptor apparatus responded to various deleterious agents. Current opinion holds that the dendrite branches of the receptor apparatus undergo alteration earlier than the transmitting axonal ramifications and their contact apparatus.

We set ourselves the task of tracing the incipient morphological processes in the interneuron connections of the cerebral cortex following exposure to low-intensity microwaves, the stages of development of interneuron connection abnormalities in relation to irradiation intensity, and the reversibility of the changes.

Investigation of the axodendral connections of the cerebral cortex in animals subjected to multiple microwave irradiation of low intensity (up to 10 mW/cm^2) revealed deformation of the dendritic branches (thickening and shortening).

As the number of irradiation sessions was increased, the branches disappeared altogether, and the dendrites developed moniliform and spherical swellings (Figure 14). The changes were especially pronounced in the apical dendrites leading to the upper associative strata of the cerebral cortex.

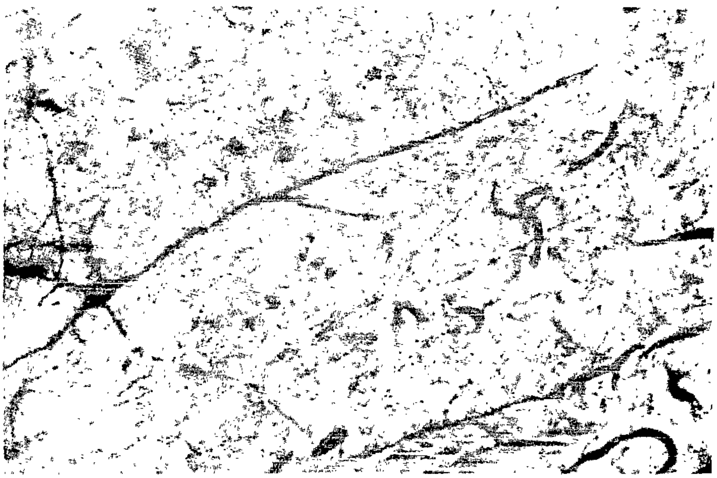

FIGURE 14. Brain. Moniliform deformation of ramifications of the apical dendrite of an efferent cortical neuron of a rat after multiple irradiations (Golgi)

The morphological changes described above were consistent with the physiological data, demonstrating disturbances of conditioned reflexes. They were functionally reversible and disappeared after the termination of irradiation, with attendant recovery of the animals' conditioned reflexes.

These effects in the axodendral connections of the cerebral cortex are neither specific nor limited to exposure with microwaves, and indeed similar phenomena in animals exposed to a variety of physical and chemical agents (arsenic, lead, aniline, etc.) were described by Tolgskaya (1954).

Axosomatic interneuron connections of the cerebral cortex, like the axodendral connections, are extremely sensitive to irradiation and show the symptoms at an early stage (earlier than neurons and the cells of internal organs). The axosomatic synapses, in which the ring and button-like structures of the axon end join with the neuron cell-body, are thickened, overimpregnated and the lumini of the rings close to form large conical structures which separate from the neuron body (Figure 15). The neurons thus undergo asynapsis. These early changes in the nerve cells may disappear on termination of irradiation, but if exposure is continued over a longer period they may become irreversible and symptomatic of destructive pathological process.

It was of interest to investigate the morphological appearance of the fine structures of the nerves in all links of reflex arcs and we have examined receptor apparatus of the skin and different receptor zones of the viscera in rabbits and rats upon microwave irradiation of varying intensity.

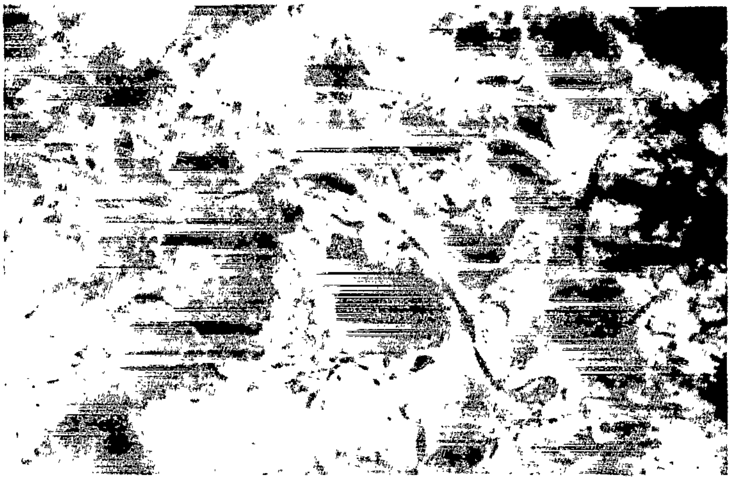

FIGURE 15. Clubbing, over-impregnation and desquamation of synaptic buttons from a neuron in the cortex of an irradiated rat (Ramon y Cajal)

The former receptors were of special interest since they are the first to experience the microwave irradiation, but the interoceptors of the viscera were also of great importance since they are reported to be very sensitive to minimal levels of various deleterious agents.

Chernigovskii (1941, 1951) demonstrated that stimuli originating from receptor fields spread to the somatic musculature, nonstriated muscles, the respiratory, circulatory, hematopoietic systems, and affect the functioning of the kidneys and adrenals and metabolism. Thus the response provoked by stimulation of receptor fields brings about a very large number of physiological processes.

According to Chernigovskii, such extensive reflexes are a characteristic feature of stimulation from interoceptors in general and from vascular interoceptors in particular.

Numerous investigators have studied changes in the receptor apparatus of internal organs in various diseases and upon exposure to a variety of detrimental agents.

Pervushin (1957) demonstrated that the receptor apparatus of the heart underwent both reversible and irreversible processes following exposure to an SHF field. The SHF field affects primarily the afferent fibers of the spinal ganglia and peripheral components of the autonomic nervous system are unaffected.

Our concept of the damage to the receptor apparatus pertains to the preterminal parts and free termini of afferent nerve fibers. Our experiments with multiple microwave irradiations of low intensity (up to 10 mW/cm^2 for 100—200 sessions) revealed that the receptor apparatus of internal organs and skin underwent transformations that could be described as irritation phenomena. These included enhanced argyrophilia, thickenings and swellings, and marked convolutions of nerve fibers; in addition to the affected nerve fibers there were also considerable numbers of normal fibers and this emphasizes the extensive compensatory capacity of the peripheral nervous system. The most marked damage was found in the receptor apparatus of the skin, effects in the other receptor zones being similar but milder.

Cells of the hypothalamic region and the spinal ganglia exhibited certain minor abnormalities such as swelling of the protoplasm and its vacuolization.

Preterminal divisions of the receptor apparatus were the most heavily affected by radiation, a finding in agreement with the data reported by Dolgo-Saburov, Kupriyanov and Pervushin.

The changes discovered in the receptor apparatus of viscera and skin upon exposure to microwaves were not specific to this agent since similar phenomena have been discovered by several authors (Lavrent'ev, 1948; Plechkova, 1948; Falin, 1948; Vyropaev, 1948; Guseinov, 1953; Tolgskaya, 1954; Sarkisov, 1964; and others) in various diseases and due to detrimental agents.

The data on damage to the receptor apparatus of viscera and skin following exposure to low-intensity microwaves agree with our previous observations of effects on the axodendral and axosomatic apparatus of the cerebral cortex, upon exposure to microwaves of the same intensity, in the absence of an overall thermal effect.

Transformations in the receptor apparatus of certain zones acting as sources of reflexes to the blood circulation and respiration, and the changes discovered in the hypothalamic region, may provide an explanation for the clinical and experimental observations of the drop in blood pressure and bradycardia following exposure to low-intensity microwaves.

Lesions of receptors and interoceptors display characteristic features according to the wavelength ranges. Centimeter and especially millimeter waves mainly affect the skin receptors, while decimeter waves left them unaffected (Figures 16, 17, 18). The interoceptor apparatus of the viscera is, however, the most heavily affected by decimeter waves.

Histochemical investigations of the animals' organs revealed a decrease of ribonucleoproteins in the cutaneous epidermis and its derivatives, most marked for the centimeter and especially millimeter waves but no change with decimeter irradiation.

Thus, irradiation with millimeter waves damaged predominantly skin receptors, with accompanying histochemical aberrations in the skin. Irradiation with centimeter waves also caused considerable histochemical changes and damage to the receptor apparatus of the skin, and in addition, similar effects on the interoceptor apparatus and the interneuron connections of the cerebral cortex. Decimeter waves affected mainly the interoceptor apparatus of the viscera, but not the receptor apparatus of the skin, and this finding agrees with the clear morphological changes in the viscera observable by ordinary morphological methods.

It is suggested that the millimeter waves are absorbed in the superficial skin layers and all the dystrophic phenomena in the internal organs result from nerve-reflex mechanisms, while the deeper-penetrating decimeter waves might affect the internal organs and brain directly and leave the skin intact. Centimeter waves may produce their effects by both types of mechanisms.

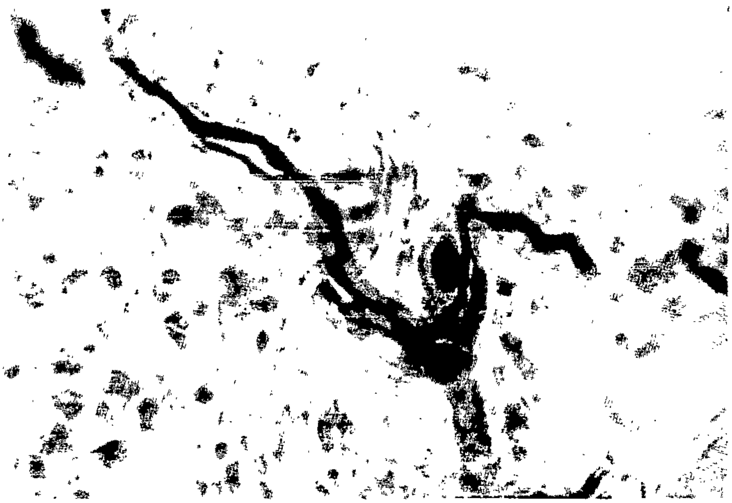

FIGURE 16. Axons of a cutaneous medullated fiber containing moniliform thickenings and swellings after exposure to millimeter waves (Bilszowski-Gross)

It is clear that the CNS is very sensitive to microwaves and there is a rather characteristic response to irradiation.

The strength of the reactions of the nervous system to microwaves and the time of occurrence depend upon intensity, the range of microwaves, the functional state of the nervous system and the animals' typological traits.

The course of reaction to microwaves was to a certain extent controlled by the initial state of the nervous system and its reactivity.

In animals with sufficiently strong and balanced nervous processes the changes in the conditioned reflexes in the initial period of irradiation with centimeter waves involved enhanced excitability of the cerebral cortex and weakened active inhibition. Continued irradiation caused a steady attenuation of excitation and strengthening of protective inhibition.

Animals with weaker excitation and inhibition processes in their normal state reacted somewhat differently to irradiation with centimeter waves. In these cases attenuation of excitation and growth of protective inhibition occurred from the first days of irradiation. Continued irradiation produced more drastic disturbances of the conditioned reflexes, demonstrating a rapid exhaustion of the working capacity of neurons.

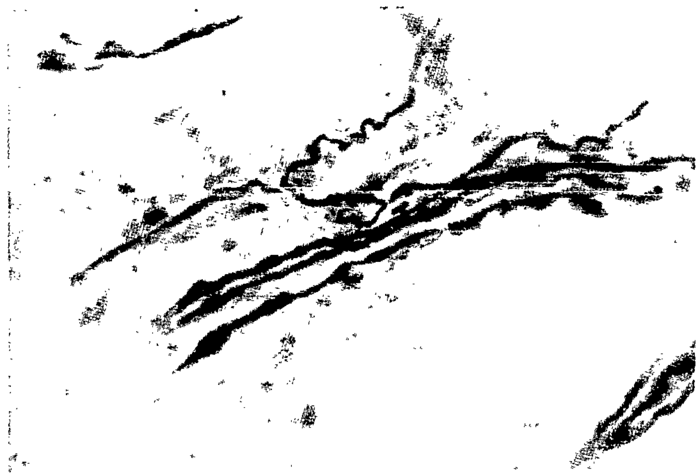

FIGURE 17. Thickening, overimpregnation and moniliform deformation of cutaneous nerve fibers upon exposure to centimeter waves (Bilszowski–Gross)

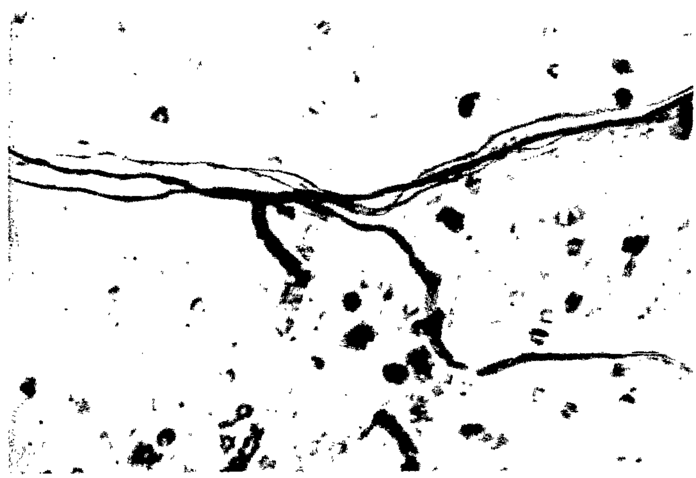

FIGURE 18. Delicate network of fine cutaneous receptor fibrils unaffected by exposure to decimeter waves (Bilszowski–Gross)

The importance of the initial state of the nervous system is emphasized by the response of rats specially sensitive to auditory stimuli. Animals which had reacted to the auditory stimulus prior to irradiation with a spasmodic attack on the first wave of motor excitation, reacted to the bell with a bi-wave motor excitation, after irradiation for one month. Animals with a bi-wave excitation reaction prior to irradiation were unaffected by the auditory stimulus after one month's irradiation.

Reaction of the nervous system to low-intensity microwaves most commonly proceeds in two phases (conditioned reflexes, cholinesterase activity, certain reactions to auditory stimulus).

Multiple irradiation with low-intensity microwaves produces persistent functional changes in the CNS, which return to normal not earlier than 30—60 days after termination of irradiation. This fact demonstrates a cumulative effect of microwave irradiation in addition to the reversibility of the process.

The foregoing data make it possible to advance suggestions concerning the mechanism of the changes in the CNS upon exposure to low-intensity microwaves.

Morphological examinations of the skin receptor apparatus and the various receptor zones of animals (Tolgskaya and Gordon, 1960, 1964) subjected to multiple irradiation of very low intensities revealed changes in the ramifications of afferent fibers. The skin phenomena are most pronounced with millimeter waves, due as already mentioned to the complete absorption of this energy. At the same time this wave range also produces changes in the CNS. One may assume that the exposure of various skin receptors to microwaves generates trains of unusual pulses proceeding to the cerebral cortex.

There are several arguments in favor of a direct effect of certain microwaves on cerebral structures, including the higher sensitivity of the isolated brain to microwaves and the persistence of its EEG reaction in comparison to intact brain, as well as more pronounced reactions of the CNS upon exposure to the deeper-penetrating 10-cm and decimeter waves. One cannot preclude the possible participation of neurihumoral factors in the body's reaction to microwave irradiation.

The response of an organism to irradiation is controlled by the range of wavelength, irradiation intensity, energy absorption by the biological structures and sensitivity of different structures of the nervous system.

Conclusions

1. The nervous system is the most sensitive part of the organism to SHF electromagnetic waves (microwaves).

2. A variety of experimental investigations with microwaves of various ranges revealed a similar trend of changes in the state of the nervous system.

3. The strength and time of occurrence of the nervous system response to microwaves depends upon the irradiation intensity and the range of microwaves in the following way:

a) the sensitivity of the nervous system to microwaves increases with increasing irradiation intensity;

b) the sensitivity of the nervous system to irradiation increases with increasing wavelength and the observed changes manifest themselves earlier and are more pronounced.

4. The course of the reaction, especially in the first period of irradiation with microwaves, is to a certain extent controlled by the initial functional state of the nervous system and its reactivity.

5. Reaction of the nervous system to microwaves often proceeds in two phases.

6. Multiple irradiation with low-intensity microwaves produce persistent functional changes in the CNS suggestive of cumulative effects.

7. Normalization of the functional and morphological changes 30 — 60 days after the termination of irradiation attests to reversibility of the process.

8. It is justified to assume that the influence of microwaves on the CNS may proceed by a direct effect on the cerebral structures as well as by reflexes from surface receptors, and through neurohumoral factors.

Chapter V

SANITARY CONDITIONS AND WORK WITH SHF SOURCES

Permissible levels of SHF irradiation intensity

The detrimental effect of SHF irradiation necessitated the establishment of maximum permissible irradiation intensities.

This may be achieved by a variety of approaches. The starting point of investigators working outside the USSR was the thermal effect of microwaves.

The following criteria were used for the determination of permissible irradiation intensities:

1. Correlation between the degree of damage to the functions of any organ or tissue, such as ocular damage, with time and intensity of irradiation (Hirsch, 1956).

However, Vosburgh (1956), Williams et al. (1956) and Carpenter et al. (1960) were all unable to establish any rigorous relationship between irradiation time and intensity on the one hand and formation of cataract on the other.

2. Correlation of the degree of damage caused to the organ or tissue with the temperature at which the damage is caused.

Attempts by several investigators at establishing such a relationship for irradiation of eyes (Richardson et al., 1948; Daily et al., 1950, 1951, 1952; Carpenter et al., 1960; Cottingham, 1960) failed; the formation of cataract was not directly controlled by the rise in the body temperature.

3. Mittelmann (1961) attempted to establish a linear-logarithmic relationship between the subjective sensation of heat by human subjects and irradiation intensity, using the frequency range from 20 to 200 Mc. He derived the relationship

$$\log H = a \log P - \log P_0,$$

where H is the strength of the subjective sensation of heat (graded according to a four-"point" scale), P is the absorbed power, P_0 is the absorbed power producing threshold thermal sensation and a is a constant independent of the frequency.

Mittelmann assumed that the P_0 values would aid establishment of safe limits of absorbed power, but it is hard to agree with this conclusion, since the effect of an SHF field is not solely controlled by the thermal effect.

4. Theoretical calculation and experimental investigations of the quantity of energy absorbed by the tissues, generation of heat and the attendant change in temperature.

Clark (1950) and Cook (1952) demonstrated that a very approximate agreement exists between calculated and experimental data (local irradiation with 10-cm waves) after brief exposure, and the role of the bloodstream in thermoregulation is insignificant in these conditions.

An approach to establishment of permissible intensities was elaborated by Schwann, Li (1956). Theoretical calculation and approximate analysis of the dependence of absorption of radio wave energy (in the frequency range from 150 to 10,000 Mc) upon the thickness of the skin and subcutaneous fat enabled the authors to infer the coefficient of absorption of centimeter waves by the body (40–50%), heat loss and possible heating of the body. They determined the PFD value (10–15 mW/cm^2) which does not raise the body temperature, and recommended the maximum permissible PFD at 10 mW/cm^2.

A large number of scientific research organizations, companies and individual experts in the U. S. A. have been concerned with the estimation of permissible radiation levels from 1953 onwards.

The problem was discussed at conferences in the U. S. A. in 1955–1958. The norm 0.01 W/cm^2 (10 mW/cm^2) was accepted by the majority of participants at these conferences. It must be pointed out that the representative of the General Electric Company (Vosburgh, 1956) proposed a safe norm of irradiation intensity of 0.001 W/cm^2 (1 mW/cm^2) and in 1958, he again proposed that the permissible intensity be reduced to 0.001 W/cm^2, arguing the necessity to allow for harmonics and spurious radiation.

In the U. S. A. and several other countries outside the USSR, the maximum irradiation level was not defined with respect to irradiation intensity and duration.

In 1961, Mumford (U. S. A., Bell System) drew up a table of permissible intensities reproduced in our Table 18. His suggestions were based on those advanced by several institutions and companies as well as by individuals (the Army, Navy and Air Force, General Electric Company, American Telephone and Telegraph Company, Bell Telephone Company, Schwan).

TABLE 18. Permissible microwave irradiation intensities (according to Mumford)

Mean power flux density, W/cm^2	Classification
> 0.01	*Potentially dangerous level*
0.001–0.01	Safe level for accidental or very occasional irradiation
< 0.001	Safe level for prolonged irradiation

The data in the table are not legal standards of permissible irradiation intensities. The minimum tabulated values approach the upper limits adopted in the USSR.

Tomberg (1961) did not object to the norm 0.01 W/cm^2, provided that the personnel were working in a space free of possible field distortions by multiple reflections, standing waves and resonance phenomena that might considerably increase the irradiation intensity.

Thus, the thermal-effect approach to the establishment of permissible wave intensities in the U. S. A. resulted in rather high PFD values.

Several workers in Poland (Minecki, 1961) and Czechoslovakia (Mahra, 1963; Sercl et al., 1961) and official authorities in these countries do not agree with the norms proposed in the U.S.A. and are guided by values adopted in the USSR, for their practical activities.

The approach to the determination of maximal microwave intensities adopted in the U.S.A. appears to us to be inadequately based. In the first place, it is supported principally by experimental calculations, which do not always accurately reflect the organism's response to irradiation, and the possible cumulation of biological effects following multiple exposures to submaximal intensities is completely overlooked. The values were calculated from short-term experiments with high irradiation intensities, which produce marked damage to the organism, by reducing the experimental intensity one order of magnitude or by only 50%.

The maximum permissible SHF intensities should be based preferably on a variety of investigations, including a hygiene evaluation of irradiation intensity under industrial conditions, clinico-physiological examinations of personnel working under these conditions, and experimental enquiries into the nature of the biological effects of SHF.

The principal criterion for the determination of maximum permissible intensities should be the response of the organism to low irradiation intensity, and the cumulative effects of long-term exposure to low PFD.

Monitoring for 6–8 years of personnel's health revealed some functional abnormalities in personnel working with SHF sources even at the minimal irradiation intensities (tenths of fractions of W/cm^2). In long-term experiments on animals, functional and morphological changes in the CNS and hypotensive effects were induced by irradiation intensities as low as 1 mW/cm^2. 10 $\mu W/cm^2$ was thus adopted as the maximum permissible level for microwave irradiation.

Detailed studies of the various technological operations involved in work with SHF sources revealed that certain activities inevitably involved exposure to somewhat higher PFD levels than others (e.g., in testing of radar units and antennas). We therefore recommended norms, differentiated with respect to intensity and duration, and the maximum permitted working time was limited to two hours for the intensity range of 0.01–0.1 mW/cm^2 (10–100 $\mu W/cm^2$).

For the next higher permissible PFD level, of 1,000 $\mu W/cm^2$ (1 mW/cm^2), the exposure time was strictly limited to 15 – 20 min during a working day. The wearing of special protective goggles was made mandatory under such conditions.

Hence, the normal permissible levels for microwaves are differentiated as follows:

1) work throughout the day is permitted at irradiation intensities not exceeding 10 $\mu W/cm^2$;

2) exposure to irradiation intensities 10–100 $\mu W/cm^2$ (0.01–0.1 mW/cm^2) is limited to 2 hr daily;

3) there is a limit of 15–20 min for work involving exposure to intensities 100–1,000 $\mu W/cm^2$ (0.1–1 mW/cm^2), and mandatory wearing of protective goggles.

In our opinion, norms of irradiation differentiated by one order of magnitude are the most rational, because of possible PFD gradients within the worksite boundaries, and also on account of the accuracy limits of the measuring apparatus.

At the present stage of investigation with different SHF ranges (millimeter, centimeter and decimeter microwaves) the question may arise of permissible levels according to wave ranges.

Indeed, the reader must now be aware that there are some differences in the biological activity of different microwave ranges. The reaction of the CNS is pronounced with centimeter and decimeter waves. In the case of millimeter waves, the hypotensive effect occurs early and the changes in the skin receptor apparatus are pronounced.

Nevertheless, the differences are not so marked that it is possible to differentiate the norms according to wavelength ranges at this stage of knowledge of the subject. This conclusion is confirmed by data on the health state of personnel working with sources of SHF in different ranges. No convincing differentiation of the clinical symptoms' long-term effect of the different microwave ranges is available. Moreover, the ultimate biological effect of long-term exposure to microwaves is as a rule identical (reaction of the CNS, hypotensive effect).

We have therefore retained integrated irradiation levels for the entire microwave range.

Measures for the protection of personnel

Comparatively few Soviet and other authors have concerned themselves with protection of personnel against SHF electromagnetic waves, since such measures necessitate the previous establishment of maximum permissible doses.

Provisions for recommendations for permissible intensities were suggested in several Soviet publications (Gordon and Presman, 1956; Presman, 1958; Senkevich, 1959; Kalyada, Kulikovskaya and Osipov, 1959; Belitskii and Knorre, 1960; Felitsin, Kogan et al., 1960; Kogan, Felitsin and Vorob'eva, 1960; Gordon and Eliseev, 1964).

The literature on this subject published outside the USSR has been concerned mainly with protection of military personnel engaged in operation of radar units.

Instructions adopted by the U. S. Army, Navy and Air Force for radar operation include demarcation of dangerous zones with respect to irradiation intensity, practical instructions on the directing of irradiation and the distance of the worksite from the radiation source (Richardson, Duane and Hines, 1951; Hines and Randall, 1952; Vosburgh, 1956; Herrick and Krusen, 1956; Egan, 1957; and others). More recent work on protection against SHF has been published by Herbert Marek (1959), La Fond (1959) Bovill (1960), Hubelbank (1960), Mumford (1961), La Fond and Gettings (1961), and others.

The authors recommended protection from high-power radiation sources by artificial means such as absorbing or reflecting materials. Vosburgh (1956) proposed a special kind of fiber board with a conducting coating reflecting $\sim 2\%$ of the radiation! The protective thin layer of common salt solution described by La Fond (1959) can be classified as an absorbing screen, although it also possesses reflecting properties. The solution is recommended for the shielding of premises. Although we are not in a position to evaluate this suggestion, it seems to us that the possibilities of a liquid screen are limited.

Other suggestions for protection against SHF radiations have included reflecting screens made of solid metal or metal netting (the latter being considerably cheaper). An exception is La Fond's optically transparent resonance screen consisting of several dielectric layers with thickness equal to one-quarter of a wavelength separated from each other by the distance $\lambda/2$. According to the author, this screen possesses considerable reflectivity for microwaves.

Attention of workers outside the USSR has been directed mainly to the protection of military radar operators, in accordance with the preferential treatment dealt to such personnel.

Personnel operating powerful radar units, for example BMEWS (Ballistic Missile Early Warning System) or ZAR (Zeus Acquisition Radar) are protected by special metal-shielded corridors interconnecting all the radar installations.

Special attention has been paid to protective equipment, including goggles and overalls made of special fabrics (Bovill, 1960; Hubelbank, 1960). We were unable to find detailed data on protective fabrics except for a nylon with silver filler, which is appparently comfortable, transparent and possesses certain protective properties.

Some authors recommend goggles made of metal netting (Richardson, 1951; Hines and Randall, 1952; Herrick and Krusen, 1956), while others regard netting as undesirable because of the potential danger of penetration and focussing of microwave energy in the eye, and such authors recommend thin films with absorbing properties.

As a result of investigations into working conditions, field experiments and actual use in many industrial enterprises for several years, we have recommended standard protective measures. Specific problems involved in the design of protective equipment and its introduction in industrial enterprises were solved in collaboration with specialists from such enterprises.

Design of protective measures was based on the following principles (Gordon and Presman, 1956):

1) reduction of radiation at the source (antenna, open waveguide, etc.);
2) shielding of the radiation source;
3) shielding of sites near the radiation source or removal of the site;
4) personal protective equipment.

Any one or a combination of these principles may be used depending upon the type of radiation source, its power and the nature of the technological process.

The protective facilities must satisfy certain technico-economic requirements, i. e., they must not cause any significant distortions of the SHF field at the antenna, they must not interfere with working convenience and they must not diminish the productivity of labor.

Reduction of radiation at the source. Suitable protective facilities must provide for convenient adjustment, tuning and testing of radar units.

1. Power absorbers (antenna equivalents) are recommended for measurements of the basic output parameters – operating frequency, spectrum width and current pulse envelope of SHF oscillations, power consumption by radar units from the mains.

Energy absorption by antenna equivalents is due to attenuation of the electromagnetic wave along the loading surface, as well as within the loading volume itself. Electromagnetic energy is dissipated and converted to heat in the substance filling the absorber volume. Various types of absorbers ensure attenuation of energy to 40–60 db (attenuation factor, 10,000–1,000,000). Absorbers may be made of graphite or carbonyl iron as fillers with different carriers (ceramic, plastic, etc.). Water absorbers are used for high and medium SHF powers.

Table 19 provides the characteristics of absorbers most commonly used in industry.

TABLE 19. Characteristics of various types of absorbers

No.	Designation	Operating range, Mc (wavelength)	SWR	Maximum absorbed power, watts	Input
1	ZAK-1-30	2,500–3,750 (12–8 cm)	1.25	30	Coaxial, 50 cm
2	ZAK-1-250	2,500–3,750 (12–8 cm)	1.25	250	The same
3	ENS-5	150–375 (2–0.8 m)	1.25	5	Coaxial, 75 cm
4	ENS-100	150–375 (2–0.8 m)	1.3	100	The same
5	UEA-5	352–666 (85–45 cm)	1.2	5	" "
6	UEA-100	352–666 (85–45 cm)	1.25	100	" "
7	EAV-1-250	2,500–3,750 (12–8 cm)	1.25	250	Waveguide, 72 × 34 mm
8	52I-E1	8,600–9,600 (3.49–3.13 cm)	1.2	250	Waveguide, 22.9 × 10.2 mm

The absorbing elements are made stepped, conical or wedge-shaped in order to attain satisfactory SWR (standing-wave ratio). Any other loads may be used in addition to the above, provided they satisfy the requirements of complete energy absorption and minimum SWR.

It is apparent from the investigations that the use of power absorbers as the load eliminates antenna which are the strongest radiation source, during the testing of radar units. The use of SHF energy absorbers made possible a revision of the specifications for acceptance of radar units and reduced the testing time by a factor of approximately 100.

This naturally solves the problem of personnel protection.

In cases where it is impossible to achieve the reduction of the testing time of radar units, the process is transferred to the factory's outdoor testing grounds.

The use of power absorbers in areas of partial tapping of energy (couplers, power dividers, ferrite rectifiers, etc.) made possible reduction of spurious radiations into the working premises by factors of hundreds.

2. Artificial target simulators may be recommended for the testing of indicator, receiver and antenna assemblies, as well as automatic and control circuits in radar units. The entire radar system works except for the

transmitter, which precludes irradiation of personnel with high intensities. The reflected signal is simulated by an artificial low-power SHF source, with the same frequency as the operating frequency of the radar unit.

The use of a target simulator practically eliminates irradiation of shop personnel, and the PFD is less than 1/1,000 of that irradiated by radar antenna, even if the personnel are located at the antenna aperture of the target simulator.

3. Waveguide couplers, power dividers, waveguide attenuators connected between the waveguide circuit and the antenna are favored during the testing of the operating regime of radar units (rotation of the unit, etc.), since they draw the radiation from the antenna devices. A smaller fraction of the power is fed into the antenna while a larger fraction is absorbed by the attenuator or else fed into the coupler or divider, which is connected to a power absorber.

In this case, irradiation reaching the personnel is diminished by the same factor as the power at the output of the antenna system.

Shielding of radiation sources is recommended for prevention of penetration of SHF energy into the working premises.

Shielding must not interfere with the adjustment, tuning and testing of the radiating device, and designers of devices must take into account the basic parameters of radiation and the purpose of the radiation source being shielded. The type, shape, dimensions and material of the shielding device vary according to the kind of radiation (direct or spurious, directional or nondirectional, continuous or pulsed) and the radiated power.

Any system used for protection against SHF energy is based on the principle of reflection or absorption of the electromagnetic energy. Complete reflection of electromagnetic waves is achieved by materials of high electrical conductivity (metals), while complete absorption is possible in materials of poor electrical conductivity (semiconductors, dielectrics with large losses).

Standard shielding devices have been constructed with regard to the type of material used, the nature and parameters of radiation source and the characteristics of the process.

Different types of screens are appropriate to the various processes, radiation sources, power and wave ranges, and include reflecting screens of solid metal, metal netting, soft metal screen with cotton or other threads and absorbing screens.

Reflecting screens are used in cases of spurious radiations (leakages from cracks in transmission lines, from cathode leads of the magnetron, etc.); reflections from the walls of the shielding device do not affect the working of the radiator.

Reflecting screens can be used for the shielding of premises, radiation sources, worksite and in protective equipment. All the screens must be thoroughly grounded.

Solid metal screens ensure reliable shielding for any practical intensities of SHF fields, according to the permissible level ($10\,\mu W/cm^2$). The screen can be of any thickness. (A screen thickness of 0.01 mm attenuates the SHF field by approximately 50 db, i. e., by a factor of 100,000.) Attenuation in solid metal screens is thus fairly high and even thin metal foil can be used to save weight.

Netting screens possess less satisfactory shielding properties than solid screens. Nevertheless, they are widely used in many situations when the required attenuation of the SHF PFD is 20–30 db (a factor of 100–1,000).

Elastic screens may be used in shielding curtains, drapings, covers and in special protective garments (coveralls, smocks, cowls).

Elastic screens are made of special material in the form of fine metal netting of mesh 0.5×0.5 mm. The fine metal wire is twisted with cotton threads which protect it against external agents and serve as electric insulation. The cotton threads fill the interstices between metal filaments and render the fabric dense and elastic. This fabric retains its protective properties at temperatures ranging from -40 to +100°C and at a relative humidity up to 98%. It can be laundered, ironed, dyed and sewn with ordinary sewing machines.

Optically transparent glass with reflecting properties can be recommended for the shielding of windows, premises, cabins and chambers, instrument panels and inspection holes. The glass is coated with semiconducting stannic oxide (SnO_2). It produces attenuation of the order of magnitude 30 db in the wave range 0.8–150 cm.

A b s o r b i n g s c r e e n s. If a process is based on the direct radiation of radiowave energy into space (e.g., in the testing of antenna devices), complete or partial shielding of the source may disturb the process or even render it impossible. Waves reflected from the screen facing the radiator will affect the operating conditions of the radar unit.

Absorbent coatings are eminently suitable in situations of this kind. The reflecting surfaces of the device are coated with a material which absorbs practically completely the energy of incident waves.

The following SHF-absorbent materials are recommended as coatings for shielding devices: rubber mats B2F-2, 3, VKF-1, molded rubber sheets of special composition with solid or hollow conical spikes (8–10 mm high); magnetodielectric plates KhV, which are porous rubber filled with carbonyl iron and filled with molded-in brass netting (mesh $< 1\ mm^2$).

Absorbent materials, for instance KhV, possess comparatively narrow ranges of effectiveness. Designers of absorbent screens for wide frequency ranges resort to multilayer systems, with an inevitable increase in weight and thickness.

The absorbent coatings are attached to the framework of the shield or protected surface mainly with special glues of the types PKhV, MS, KhVK-2a, No. 88, etc., (Krylov and Solovei, 1961).

A shielding device may be in the form of:

a) shielding chamber (closed screen);

b) open screen.

Shielding chambers, completely surrounding the source, are used for nondirectional spurious radiation, mostly of low intensity (leakages from cathode leads of the magnetron, in flange connections of the waveguide circuit, etc.).

Closed screens include the shielding casing used for the tuning of aircraft radar antennas on the ground. The casing is a metal hood with an absorbent coating which is put over the antenna windshield.

When it is necessary to observe the working of an entire generator assembly during the adjustment of trial units (inspection holes are not always adequate for this purpose), the sheet-metal cover and doors of the cabinet may be temporarily replaced with metal netting.

Shielding chambers are also recommended for various manufacturing processes involving directional radiation, such as in the testing of irradiators for dielectric breakdown, for which the irradiation intensity at the source is high. Shielding with a double chamber of metal netting or solid sheet metal may also be necessary in this case.

The dimensions of the shielding chamber are controlled by those of the radiation source, the working premises and convenience. The minimum dimensions are governed primarily by the radiated power.

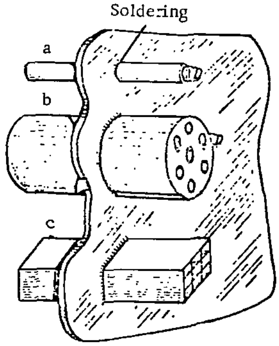

FIGURE 19. a, b, c are apertures in screens of the "critical waveguide" type

If the power of the source, the type of process or chamber size dictates it, the absorbent coatings may be used over the entire inner surface or over some areas, depending upon the direction of radiation.

Designers of shielding chambers for cabinets of generator assemblies, SHF units and devices must provide for inspection holes, doors, apertures for power-supply leads, etc.

The apertures may be divided into the following three main types according to the conditions of penetration of the SHF electromagnetic energy:

1. Small apertures of various shapes (without metal leads passing through them), of which the maximum cross section is smaller than the critical value for the operating wavelength (i. e. inspection and ventilation holes); such apertures are sections of critical waveguides.

2. Small apertures with power supply wires or metal control knobs passing through them are sections of coaxial lines.

3. Slots with longitudinal dimensions larger than the wavelength (door perimeter, ventilation blinds, etc.).

A p e r t u r e s o f t h e "c r i t i c a l w a v e g u i d e" t y p e. The length of the tubes of critical waveguides is controlled by the required energy attenuation factor and the tube's attenuation factor.

For tubes of circular cross section (Figure 19, a, b), attenuation per 1 cm length is calculated from the formula:

$$\alpha = \frac{32}{D}\ \text{db/cm},$$

where D is the tube diameter, cm.

For tubes of rectangular cross section (Figure 19, c), attenuation per 1 cm length is calculated from the formula:

$$\alpha = \frac{27}{a}\ \text{db/cm},$$

where a is the side of square or the longer side of the rectangle, cm.

The quotient obtained by dividing the required attenuation by the attenuation per 1 cm length of the tube represents the minimum permissible length of the tube.

The above formulas are valid providing the operating wavelength of the generator assembly considerably exceeds the critical wavelength of the circular or rectangular critical waveguide.

If several apertures are necessary, the total power leakage may increase by the same factor.

In practice the degree of shielding is higher than the calculated value because of heavy power reflections from the screen.

In cases when it is necessary to insert control knobs through apertures in screens, the critical waveguides are filled with dielectrics and the attenuation in the critical waveguide becomes somewhat smaller on account of the higher dielectric constant (ε) of the material of the knobs in comparison to that of air (1).

Attenuation in apertures filled with a dielectric is calculated from the following formulas:

$$\alpha = \frac{27}{a\sqrt{\epsilon}} \text{ db/cm for a rectangular aperture}$$

and $\alpha = \dfrac{32}{D\sqrt{\epsilon}}$ db/cm for a circular aperture.

Apertures of the "coaxial line" type, in contrast to the "critical waveguide" type, offer practically no resistance to energy conduction in any wave range, however small their cross section.

Therefore, special shielding measures should be devised for coaxial leads. One technique for coaxial leads is to fill the space between the central and outer conductors with absorbent materials, such as carbonyl iron or graphite, which produces attenuation of the order of magnitude 1 db per centimeter length of coaxial line. In practice it is always possible to achieve the necessary attenuation because the coaxial line used for supplying the mains voltage to the shielding chamber can be made sufficiently long.

Metallic control knobs inserted through the screen can be designed on the same principle.

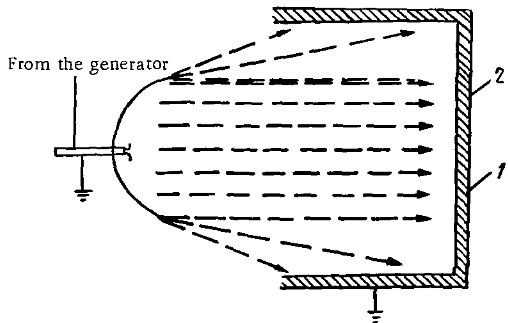

FIGURE 20. Open U-shaped screen:

1 – screen; 2 – absorbent coating.

Leakage of high-frequency energy via coaxial apertures may also be reduced by means of special filters.

The simplest coaxial filter consists of a connection of two coaxial lines with sharply different wave resistances. Such a connection of coaxial lines usually ensures power attenuation > 10 db (by a factor of 10).

Apertures of the "slot radiator" type. Slots considerably longer than the critical dimension are narrow waveguides in which electromagnetic waves are propagated with relatively small attenuation (ventilation blinds, slots in doors, etc.).

One technique for attenuation of such radiation involves special quarter-wave filters, which are grooves of depth $\lambda/4$. Such filters reduce the penetration of SHF energy by more than 10 db. Their narrow wave range is a disadvantage.

A more efficient shielding method for slots over a broad range of wavelengths is the use of absorbent lining over the entire slot length, or else provision of close electric contact over the entire slot perimeter.

Open screens. Directed radiation is mostly encountered in the testing of radar units, antenna devices, components of the SHF circuit for elimination of electrical breakdowns, etc.

The majority of operations involving directed radiation require the testing of antenna devices (drawing the radiation pattern and measurement of frequency characteristics). Although these investigations are most commonly performed at low-power levels, supplied by measuring generators (up to 5 watts), the irradiation intensity may be considerably in excess of the permissible PFD values.

Various forms of open screens made of a variety of materials can be used, according to the nature of the work. We may mention the flat and U-shaped screens that have been introduced in practical work and have completely justified themselves. The former may be permanently fixed or portable, in the form of a shield or coating on the wall at which radiation is directed, and are made of material reflecting or absorbing SHF energy (the choice is controlled by the nature of the manufacturing process and the location of worksites).

Figure 20 shows a U-shaped screen for a source of directed radiation (antenna).

The main directed flux is absorbed in the coating and does not penetrate beyond the screen placed opposite the antenna. Radiation directed at an angle to the main flux is absorbed by the coating on side walls.

The shape, size and material of an open screen must be chosen in each case such that personnel working in the room are not exposed to irradiation of intensities exceeding the maximum permissible level. One must consider the possible irradiation by reflection, as well as from other sources located in the same room.

Shielding near the radiation source. Protective devices for personnel working with radiators. Shielding of the worksite is essential when attenuation of radiation directly in the radiating device or shielding of the latter is technically impossible.

In some cases such shielding does not involve any particular difficulties. The worker engaged in the testing of the radiating device must often stay within the radar cabin which is covered with metal. Testers occupied in the tuning and testing of radar units in the shop or on open testing grounds and radar operators on airfields and in other installations are examples of such people. Obviously radiation may penetrate into the cabin via open doors and windows. In such cases, the cabin is arranged in such a manner that its doors open on the side away from the radiating antennas. If this is impossible, the windows must be made of protective glass or covered with metal netting and the cabin doors kept closed during the radiation period.

For some processes, the worksite may be shielded from the radiation source with an open screen.

Figure 21, a, b, shows screens for various locations of sites with respect to the radiation source.

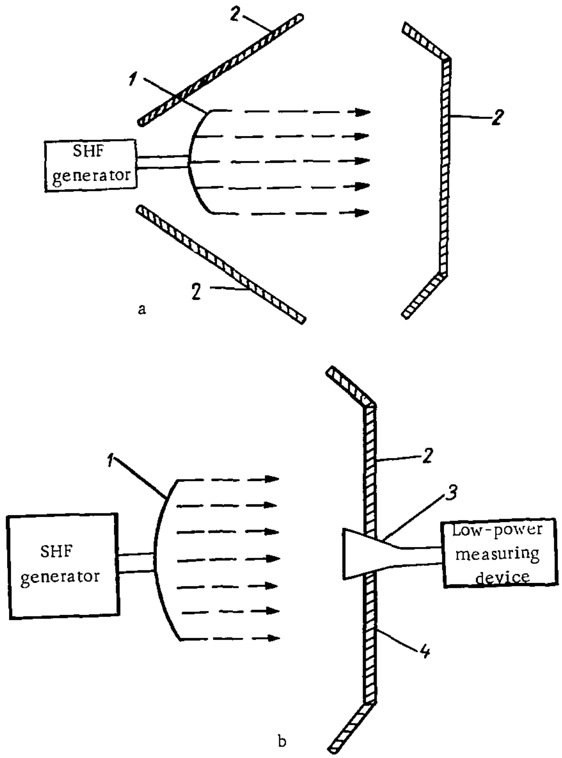

FIGURE 21. Shielding of a worksite:

a – worksite located behind the radiation source (1. antenna; 2. screens); b – worksite located in front of the radiating device (1. antenna; 2. screen; 3. horn; 4. absorbent material).

In the first case (see Figure 21, a) the site is located behind the source, e.g., the antenna mirror. Such a location may occur in the adjusting and testing of immobile radar assemblies. The first step in preventing irradiation of personnel is elimination of reflection from the screen, which should be rendered absorbent with respect to SHF energy; in addition, shields covered with absorbent material should be placed on both sides of the antenna for absorbing energy from side lobes.

In the second case (see Figure 21, b), the site is located in front of the radiating device, when, for example, the radiation pattern of an antenna is being determined.

In this case, the screen should be placed at a distance exceeding 6 wavelengths from the radiator and thus avoid significant distortions of the results.

Protective devices in the testing of waveguide circuits for electric strength. As was shown in the section on work hygiene, a very high percentage of total work consists of adjustment and elimination of sparking, electrical breakdown and corona in the waveguide circuit components, such as the rotating adapters, waveguide switches, etc. Since the operation of magnetron generators for loaded circuits does not make possible the determination of the location and nature of sparking, open matched horns are often used and these generate considerable irradiation intensity. In our laboratory, Belitskii and Knorre (1960) recommended special devices to overcome such dangerous irradiation, in particular of the eyes. These methods make possible the observation of sparking in the waveguide when the bulk of magnetron power is fed to the load.

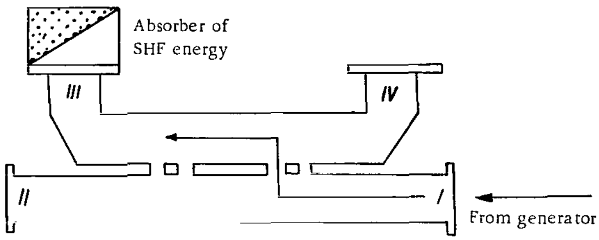

FIGURE 22. Slot waveguide bridge

Figure 22 demostrates a device based on the properties of slot waveguide bridge. Power from the generator proceeds via the arms I and III to the load, while arms II and IV make possible observation of electric breakdowns in the waveguide circuit.

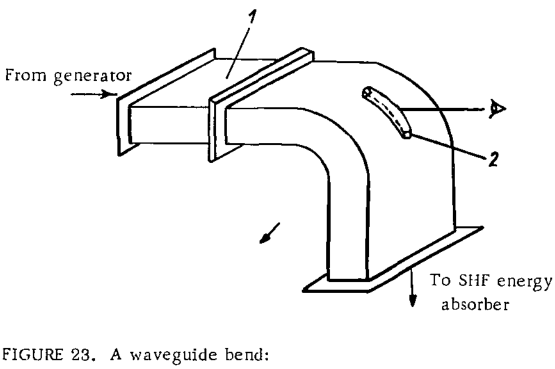

FIGURE 23. A waveguide bend:

1 – component being tested; 2 – aperture of the "critical waveguide" type.

Also in use is a waveguide bend in the plane E with a slot in the central portion of the broad wall of the waveguide (Figure 23). The slot must be based on calculation of the critical waveguide.

A third method is based on control and recording of the current pulse envelope of SHF oscillations of the refracted signal, by breakdown in the circuit (Figure 24).

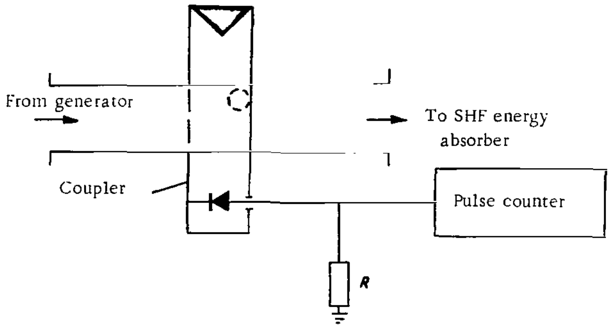

FIGURE 24. Diagram for monitoring breakdowns in the circuit

The scheme consists of a direction coupler for tapping part of the reflected SHF power; the power in the coupler sleeve is proportional to the power reflected in the high-frequency circuit. When breakdown in the circuit occurs after the coupler, the energy in the sleeve will increase with a corresponding increase in the amplitude of the current pulse envelope of SHF oscillations rectified by the diode. An amplitude rise above the permissible level triggers the circuit which counts the electric breakdowns in the circuit.

The method ensures telemetric monitoring and counting of the number of breakdowns.

Personal equipment recommended against SHF energy includes special protective goggles which are necessary for irradiation intensities exceeding 0.1 mW/cm^2 and special protective garments (a smock with cowl) for extraordinary situations, mostly for brief experimental investigations involving exposure to high irradiation intensities.

Protective goggles are designed to protect the eyes against the detrimental effects of SHF energy in the PFD range 100–1,000 μW/cm^2 (0.1–1 mW/cm^2) and higher.

The requirements that must be met by the goggles depend upon the required attenuation of the incident PFD and the wave range.

In 1956, the following two types of goggles were proposed by the Institute's laboratory:

1. Netting goggles designed as a half-mask, their "eyes" being made of fine-mesh brass netting. The wire diameter is 0.07–0.14 mm and the meshes are 560–186 per cm^2, respectively. The goggles produce attenuation of 30 db in the range of 10-dm waves. Their frame is made of an absorbent material.

2. Goggles of the airman-driver type (technical specifications TU 736-49), made of glass coated with a thin layer of gold (thickness 0.3 micron)

ensuring satisfactory transparency. The coating is deposited by cathode dispersion in vacuum and then protected with transparent varnish. The frame of these goggles is covered with protective fabric of shielding properties (Figure 25).

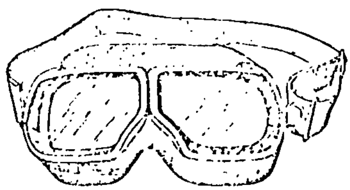

FIGURE 25. Protective goggles

Netting goggles became fairly popular and have remained in use to this day, with certain modifications.

In 1961, Kogan, Felitsin and Vorob'eva proposed special goggles of the airman-driver type (technical specifications TU-736-49) for protection against SHF energy; their glass is coated with a transparent film of semiconducting stannic oxide (SnO_2).

These goggles attenuate SHF power by at least 30 db in the wavelength range 0.8–150 cm. Transmission of the glass for light is not below 74%. The mechanical strength of the film is not inferior to that of the glass itself and the film is chemically stable, being attacked only by hydrofluoric acid. The frame of goggles is made of porous rubber and is covered on the outside with a fabric (attached with glue) having shielding properties.

These goggles which differ from the preceding type in that the glass is coated with a film of stannic oxide are currently the most satisfactory. They are commercially manufactured by the Suksun optico-mechanical factory.

Protective measures against SHF irradiation for testing grounds and airfields. Work with SHF sources outside the shop or laboratory premises has distinctive features.

We usually recommend that all testing of radar units involving radiations of high power be transferred from factory shops to open testing grounds. This measure limits the number of personnel who may become exposed to irradiation (i. e., personnel directly concerned with the tests and those not working with radiation sources or even working in other premises).

Irradiation of personnel directly concerned with the tests is reduced by absence of reflection, an increased working area and the possibility of complying with boundaries of irradiation zone, etc.

The principal method for protection of personnel working outside the factory shops (on factory testing grounds and airfields) against SHF irradiation consists in the correct arrangement of the antennae which are the radiation sources. This is especially true in the case of radar units designed for complete rotation. One must emphasize, however, that the use of power absorbers (antenna equivalents) for certain testing periods should not be relinquished.

The radiation zone must be determined for every source separately, taking into account the permissible irradiation levels. With several sources irradiating simultaneously, the possibility of cumulative exposure should be taken into account.

The radiation zone can be determined by calculation, based on known parameters of the radar unit and the width of the irradiation pattern of the antenna; but measurement of PFD at the maximum output of the irradiation source is also essential. Care should be taken to check that radiation zones from several radar units do not overlap and that the total PFD does not exceed the permissible irradiation intensity. Boundaries of zones in which the permissible levels are exceeded should be marked either with fencing or with warning signs.

The radiation zone should be reduced by raising the radiating block of the radar unit as high above the ground level as possible. This may be achieved by embankments of the maximum possible height, special towers for small antennas and roofs of observation stations.

If the radar unit cannot be raised onto an embankment or tower, the maximum positive antenna tilt angle should be used.

Any screens (reflecting or absorbing) may be used as shielding devices, including solid metal corridors between radar stations.

Protective screens should be used to shield sites which may be periodically encompassed in a radiation zone. This requires portable screens for protecting personnel assembling neighboring radar units and especially their antenna systems, shielding huts used for permanent observation stations, the correct orientation of the doors of metal cabins of radar units with respect to radiation sources, and metal netting for the shielding of the cabin windows and also their door apertures are necessary.

Finally, factory testing grounds should under all circumstances be transferred from the factory grounds to areas outside the boundaries of populated areas.

All the above recommendations for protection against detrimental effect of microwaves apply to any SHF generator, including radar generators and SHF generators for measurements and other operations in shops and laboratories.

These measures are fairly effective. Irradiation, for example, is diminished by 50–60 db by absorbers of SHF energy. Closed screens with an absorbent coating or shields with absorbent coating provide efficient protection to the extent of 30–50 db; finally, other protective facilities reduce the PFD level by 10–30 db (by factors up to 1,000).

Hence, recourse to protective technical and administrative measures makes possible the reduction of irradiation at sites to within permissible levels.

Curative-preventive measures

The Soviet legislation prescribes preliminary and periodic medical examinations for prevention of occupational diseases. Preliminary medical examinations of candidates for jobs involving work with radio-frequency generators must be guided by contraindications to employment of personnel for work with UHF.*

A neuropathologist, an internist and an oculist must take part in the preliminary and periodic medical examinations.

* Order of the Minister of Health of the USSR, No.136-M of 7 September 1957, and list No.52 in Appendix 2.

Participation of other specialists in cases of need is also necessary.

Examinations should include peripheral blood tests such as WBC and thrombocyte counts, ECG investigations and X-raying of the chest. For early detection of ill effects of irradiation, histamines, protein and protein fractions of the blood and functional activity of the thyroid gland (with radioactive iodine), etc., must be examined. The eye should be examined opthalmoscopically and with a slit lamp.

Periodic medical examinations should be performed annually, and at shorter intervals for some of the medical indexes.

Symptoms of effects due to long-term exposure to radio-frequency electromagnetic waves detected in the course of medical examination call for outpatient or inpatient symptomatic and recuperative treatment. The physician may likewise recommend treatment in a sanatorium or health resort. After rehabilitation, the subjects may return to their work provided they are kept under proper medical observation.

The changes in the organism produced by exposure to radio-frequency electromagnetic waves being reversible, the periodic medical examinations may determine the need for temporary transfer to another kind of work which does not involve irradiation by radiowaves. Transfer to another kind of work should not be limited to cases showing pronounced effects of radio-frequency fields, but in all cases of general diseases which may be affected by exposure to irradiation.

Personnel with pronounced form of diseases resulting in persistent impairment of working capacity should not continue working in conditions involving exposure to radio-frequency electromagnetic waves.

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